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A PRELIMINARY DESCRIPTION OF THE NIGERIAN LEAD–ZINC FIELD.

J. L. FARRINGTON.

ABSTRACT.

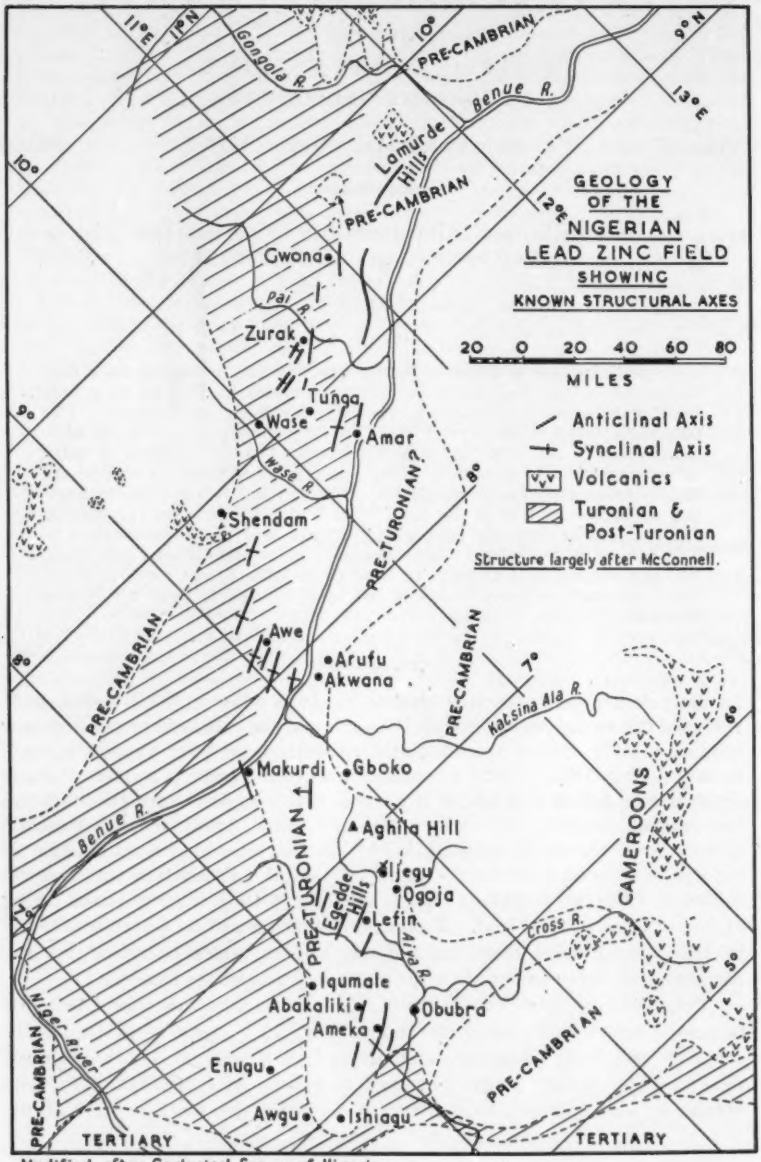
Deposits of lead and zinc in the Cretaceous rocks of Nigeria have been known for a long time but have only been mined in the past on a very small scale owing to difficult communications and low metal prices. This large field, over 30,000 square miles in extent, containing several score occurrences of lead and zinc minerals has not yet been mapped in detail or comprehensively described. This paper gives a short account of the history and a preliminary description of the physical features, the geology, and the mineralization of the field. The lead-zinc veins are regarded as occurring in structurally controlled fractures and the mineralization to have been of hydrothermal origin deposited under mesothermal conditions. The mineralization is thought to have taken place before the end of the Turonian stage of the Cretaceous and to be related to small but widely distributed dioritic intrusions.

INTRODUCTION.

IN the past five years renewed interest has been taken in the Nigerian lead-zinc field due to the demand for these metals and the enhanced prices they now command. The earliest recorded modern working of these deposits appears to have been in 1885. Local inhabitants worked the outcrop sections of many deposits long before that and it is possible that the early Portuguese traders took a hand in mining the southern region. Zurak, Arufu, and the Abakaliki district were the main localities known at the time of the initial mineral surveys of Nigeria between the years 1904–1909. Production was first recorded in 1925 and continued on a small scale to 1937 when it ceased owing to the very low price of lead. Production recommenced on a very small scale in 1947. At present there are not any milling plants operating but exploration and development are in progress in a number of localities.

This lead-zinc field extends some 350 miles in a narrow inland belt that is poorly served with communications (Fig. 1). Portions of the southern end have been topographically mapped to a scale of 1/125,000 while the remainder is only roughly mapped to a scale of 1/500,000. The Coal Measures, and adjacent formations, that overlie the southern end of the

FIGURE 1.



Modified after Geological Survey of Nigeria.

lead-zinc-bearing horizons have been geologically mapped in some detail; otherwise, with few exceptions, geologic mapping has been mainly of a reconnaissance nature. More detailed mapping is now in progress in selected areas.

A comprehensive description of this field has not yet been published. Mackay (15) [1] gave a brief summary at the International Geological Congress in 1948; McConnell (1949), then of the Geological Survey of Nigeria, and Tattam (1950) prepared reports which were not published, covering many aspects of the geology and mineralization. In addition to their publications on the geology of the Cretaceous, the Geological Survey of Nigeria have a considerable fund of unpublished information, and new work is in progress. One oil company and a number of mining companies have been operating in different parts of the field for varying periods. Until recently all this work was of an exploratory nature; more specific investigations are now in progress in selected localities. A large fund of information has accrued from the activities of these companies and the Geological Survey, but much work remains to be done before a well substantiated account of the field can be given. This paper presents a preliminary description, which will need modification and amendment as new knowledge is acquired. It is based on the results of exploration done by Amalgamated Tin Mines of Nigeria Ltd. under the author's direction and the published and unpublished work of the Geological Survey, with additional information from many sources. Descriptions of individual mineral deposits are omitted because none are adequately opened up as yet and no opinion is offered as to the potentialities of the field at this early stage in its development.

Acknowledgments.—The author wishes to record his sincere thanks to the Board of the Amalgamated Tin Mines of Nigeria Ltd. for permission to publish this paper. In the course of its preparation he has had the kind co-operation of the Director of the Geological Survey of Nigeria, and the Chief Inspector of Mines, in obtaining access to unpublished data, and to these grateful acknowledgment is made. The author has also had the special advantage of personal communications with many other workers in the field: officers of the Geological Survey, officials of various mining and oil companies, and Dr. C. M. Tattam when he revisited Nigeria on behalf of Amalgamated Tin Mines of Nigeria Ltd. in 1950. He is also indebted to the Director of the Geological Survey, Dr. R. R. E. Jacobson, and to Mr. F. A. Williams, Senior Geologist, Amalgamated Tin Mines of Nigeria Ltd., for many helpful criticisms.

HISTORICAL SUMMARY.

No record has been traced of the earliest activities in this field. There is a certain amount of semi-legendary tradition narrated by natives, apart from which one can only draw deductions from the old excavations. Just when native working commenced is unknown; in several localities it must have have been generations ago, while in a few the local inhabitants have only recently taken an interest in nearby occurrences of galena. Nowadays native

[1] Numbers in parentheses refer to Bibliography at end of paper.

mining is done entirely for cubical galena which is used as a cosmetic. While this use is not new it is almost certain that native mining before the advent of European traders was quite largely, if not mainly, for the purpose of obtaining iron. Slag is often found in the spoil near old workings and large slag heaps have been found in the Abakaliki district. Digging implements have been found in collapsed workings as much as 30 feet below the surface. These implements, small iron picks with heavy wooden handles, are not unsimilar to those still in occasional use in some parts of the field and are not of any antiquity. Native methods of mining were crude and probably spasmodic: they made open excavations in the oxidized zone with a limited amount of irregular tunnelling near the water table. The use of timber for support, or fire and water for rock breaking, seems to have been very little employed. Descriptions of native workings from the early days of European occupation and observation of current workings show that water was the limiting factor in such mining. The oxidized siderite-sulphide lodes were sufficiently soft to be mined by crude methods, whereas the highly siliceous lodes were too hard and did not normally contain enough iron or galena to be worth working.

The course of mining in any district, particularly in the moslem north, was often governed by the whims, superstitions, or cupidity of the reigning chiefs and must have been affected by inter-tribal wars and the shifts of population. The prohibition of mining and the concealment of working places in specific localities by past chiefs is still related by old natives.

It is probable that there are not any outcropping veins that were not known to the natives at some time in the past, and many veins that do not now show at the surface were once worked. Much of this knowledge came from the cultivation of the soil, particularly near the southern end of the field where so much of the land has, at one time or another, been piled into yam heaps and any glistening galena would be noticed. In the less populated central portion of the field elongated shallow depressions flanked by low rubbly mounds are the usual surface conditions over veins of which the outcrop sections have been mined. Here the soil and lateritic clay overburden averages about six feet and it is likely that some form of prospecting was necessary to locate many of the veins. From the time of the first native mining to the present, much interest has been shown by them in occurrences rich in iron and/or galena. Although the history and often the location of many occurrences have been forgotten, intensive work was done on the surface sections of practically all the iron and galena-rich outcrops.

Iron was smelted from some of these outcrops until the advent of European trade brought easier supplies of the ready made metal. Cubical galena has long been prized as a cosmetic in Nigeria. Non-cubical varieties are valueless for this purpose and many natives refer to it as "zinki." There is still a moderately large trade in galena as a cosmetic and it is sold in all the larger markets of Nigeria. In the southern part of the field lead was smelted from galena for use as fishing net weights, a use that was discontinued when supplies of the imported metal became available. There was a small silver ornament industry at Arufu until late in the nineteenth century.

The first record of European mining dates from 1885 when, it is stated in the Muri Gazetteer, there was a mining camp at Arufu where a considerable pocket of silver was discovered and worked out. Mining companies started pegging ground at Zurak, Arufu, and in the Abakaliki district shortly before World War I but the first production was not recorded until 1925 when the Zurak Mine commenced shipping concentrates. This mine continued producing silver-rich lead concentrates until 1937 when the proportion of galena in the ore and the grade of silver fell below the then economic limit. During the life of this mine the price of lead was so low that only high silver ore was

TABLE I.

NIGERIAN PRODUCTION OF LEAD AND ZINC CONCENTRATES.

Year	Lead concentrates	Zinc concentrates	Remarks
1925	90 tons		
1926	240		
1927	316	21 tons	
1928	31	124	
1929	71	—	
1930	561	21	
1931	2,015	—	
1932	683	—	
1933	979	—	
1934	675	—	
1935	1,160	—	59.5% Pb conc. 120 oz. Ag.
1936	1,275	—	65.1% Pb conc. 120 oz. Ag.
1937	851	—	65.1% Pb conc. 120 oz. Ag.
1938 to 1946	Nil	Nil	
1947	91	10	£832 value.
1948	345	541	£22,669 value.
1949	36	109	
	9,419	826	

NOTE: The 9,383 tons of lead concentrate produced from 1925 to 1948 was valued at £109,174 or an average of £11.63 per ton.

profitable. Arufu did not have any recorded production. A fair amount of prospecting was done in the Abakaliki district and some 660 tons of lead concentrates were produced from there between 1925 and 1929. In 1937 all operations were suspended owing to the low price of lead and the difficult communications. With the higher price of lead in 1947 renewed interest was taken in the field and exploration and development are now in progress. A small production has been recorded since 1947 but this does not come from properly organized mines; no milling plants are in operation at present. Table I gives the recorded production from 1925 to 1949.

PHYSICAL FEATURES.

Terrain.—The main belt of the older Cretaceous occupies a long low-lying tract bounded irregularly to the northwest and southeast by higher rougher country. The wide sandy bed of the Benue River provides the major feature in the northern and central parts but is absent from the southern. In the northernmost portion there are many steep-sided sandstone hills and ridges; otherwise there are few topographic features of note.

The southernmost section, between Ishiagu and the Egedde Hills, consists of undulating to rolling country, rather less than 400 feet above sea level, with a number of small rounded hills and low ridges. It is bounded to the west by the Awgu escarpment and to the south by low sandstone scarps. It is drained by several sprawling stream systems southwards to the Cross River. In the center of the northern end of this section lie the Egedde Hills, a compact, steep-sided, well forested group of hills rising to just over 1,200 feet above sea level. The southern boundary of this region practically corresponds with the northern limit of the coastal forest belt. There are small relic patches and strips of forest within the area, mainly following watercourses. Otherwise the vegetation is of the savannah type, consisting of scattered small to medium sized trees with irregular areas of more open country where cultivation has been more intense. Except after the annual dry season fires, there is a dense growth of tall grass, scrub and young trees.

From the Egedde Hills to the Benue River at Makurdi the country is gently undulating with very few features, the central watershed lying from 400 to 600 feet above sea level. There are a few low hills, especially around Aghila Hill, but the main features are low, sweeping, laterite scarps resulting from the dissection of a once extensive laterite sheet. The drainage is by slow winding streams northward to the Benue and southward to the Aiya River. The vegetation is savannah type with an occasional stand of high open forest. There is a tall thick annual growth of grass with which undergrowth occurs extensively only along the southeastern margin between Ijegu and Lefin. From this area northwards the annual fires burn the grass clear, except when the grass is fired before it is properly dry.

From Makurdi to the Pai River there is the broad basin of the Benue rising gradually away from the river at about 400 feet above sea level to elevations of 800 to 900 feet. The ground undulates very gently between broad low divides and shallow depressions in which only the major stream courses are well defined. The monotony of the landscape is occasionally relieved by low ridges and a few prominent steep-sided conical or cylindrical hills, the most striking being Wase Rock, the sheer sides of which rise several hundred feet above the surrounding country. The drainage is directly towards the Benue by braided systems of meandering streams most of which flow only during the rains. The vegetation is of the savannah type, scattered trees, and thick tall grass with occasional stands of higher trees.

Northeast of the Pai River there is much more relief. Nearer the Benue River the curved, generally steep-sided, stony ridges of the Lamurde and Ligri hills, rising to over 2,000 feet, dominate the landscape. Farther north

in the Gongola region there are many scattered hills and ridges, the highest being Tangale Peak (3,000 feet). Precipitous flat-topped hills are quite common in areas of flat-lying sandstones. Otherwise, most of this section is rolling country with an average elevation of some 1,200 to 1,600 feet above sea level, falling to under 800 feet in the valley of the Gongola. The drainage is principally by the Gongola River and its tributaries, nearly all of which flow only during the rains. The vegetation is savannah type with a high proportion of thorn bush in places. The grass growth is heavy but not as luxuriant as in other parts of the field.

Climate.—The climate is tropical with two distinct seasons, the rains from May to October with the remainder of the year more or less dry. The rainfall decreases progressively in quantity from southwest to northeast: from Awgu to Makurdi the average annual rainfall is between 60 and 70 inches (rather more around Ogoja); from Makurdi to Wase it is between 45 and 60 inches; the rest of the field has 35 to 45 inches. Absolute shade temperatures range from 45° to 110° F with an annual mean of about 80° F.

During the rains, the daily temperature range is small, the humidity is moderately high, and the climatic conditions are not unpleasant. From November to February the dry dust-laden "Harmattan" blows from the northeast causing a big drop in the humidity, which is accompanied by extremes of temperature. This wind diminishes in strength and effect towards the southern part of the field. In the months before the rains the humidity rises again and high temperatures are the rule throughout the 24 hours. Severe electrical storms are common and tornadoes are liable to occur during the early rains.

Population.—Although Nigeria generally is densely populated by African standards, most of the lead-zinc field lies in the less well populated parts of the country. The southwestern corner is heavily populated with over 200 per square mile, a figure which decreases steadily until, just south of Makurdi, it falls to below 100 per square mile. The country between Makurdi and Gwona is sparsely populated (under 50 per square mile) with a few uninhabited tracts. In the Gongola region the figure varies from 50 to 100 per square mile.

There are many tribes inhabiting the field, some occupying quite small areas. Up to sixty years ago migrations, due largely to inter-tribal warfare, were more or less continuous and one finds several enclaves removed from the main tribal areas. Superimposed on the local negroid types there are many settlements of moslem Hausas and Fulani and the nomadic Fulani herdsmen roam over all the territory north of 8°N lattitude. The southwest corner is peopled by the Ibo tribes and from the Egedde Hills to the Benue River the country is occupied by Tivs with Idomas to the west. From Makurdi northeastwards there are a large number of pagan tribes. In this region there are areas principally peopled by Fulani and there are some Hausas settlements, chiefly in the larger towns. Contact with the Mohammedans has resulted in some semi-conversion of the indigenous pagans.

There is practically no skilled labor available within the field except at Enugu. Artisans and clerks are available from other parts of Nigeria. Un-

skilled labor is available in moderately large numbers in most localities except during the planting season just before the rains.

There are not any permanent white inhabitants: those residing in the field are government officials, employees of mining or commercial firms, and a few missionaries. At Enugu there is quite a large white community; elsewhere there are a few dozen scattered on small stations, nearly all south of Makurdi.

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General.—The Nigerian lead and zinc deposits, with a few minor exceptions, all occur in rocks of lower Cretaceous, or, at the latest, Turonian age. The exceptions are situated to the northwest in the crystalline rocks. The main belt of the older Cretaceous formations in Nigeria appears in the southwest from under the cover of younger sediments at the base of the Awgu escarpment, south of Enugu. From here, it stretches in a north-north easterly direction for 150 miles to the Benue River at Makurdi, thence in a north-easterly direction following the Benue valley for a further 300 miles. This belt covers an area of some 30,000 square miles.

There is an arm of these sediments that branches eastwards for 80 miles from the main belt up the Cross River valley. The eastern end of this arm has been described by Wilson (8). There are not any significant mineral deposits known and these exposures are not described here.

The strata of the main belt are folded, in places quite severely, faulted, and invaded by many intermediate to basic intrusions. The southwestern third of the belt is composed mainly of argillaceous sediments whereas the remainder is distinctly more arenaceous. Conglomerates are noticeably rare throughout and limestones are not abundant. Probably all of the sediments as far north as the Pai River are of marine or deltaic origin; beyond the Pai, terrestrial facies begin to appear and soon become predominant. In general, the appearance and characteristics of these older Cretaceous formations bear many points of resemblance to considerably older rocks in other parts of the world.

Outcrops are generally meagre to scarce except in the northeast and in certain parts of the southwest. In the hilly parts of the northeast outcrops are plentiful and in the rather more dissected southwest, from the Egedde Hills to Awgu, they are moderately common; elsewhere rock exposures are scarce.

Stratigraphy.—As far as is known the Cretaceous rocks of Nigeria rest everywhere on a crystalline Precambrian floor, principally granites and gneisses. Sediments and volcanic rocks of intervening age are unknown. The contact at Semende, just north of Gboko, shows Albian limestones lying unconformably on crystalline rocks in a sharply embayed manner. Several other unconformable contacts are known and many apparent low angle overlaps of sediments over crystalline rocks can be seen on aerial photographs. In one locality in the extreme northeast, Turonian sediments come in contact with crystalline rocks along a normal fault, which is oblique to the general trend of the contact. Nowhere does this sedimentary basin show evidence of

rifting. The natural condition appears to be one of normal unconformability throughout. In view of: (a) their disposition in a long narrow belt, with another belt at right angles following the Niger valley; (b) the longitudinal folding; and (c) the roughly medial arrangement of the associated intrusives it is possible that the Cretaceous formations were deposited in a geosyncline. On the other hand Tattam (II) considers that the preservation of these sediments is probably due to Tertiary warping.

The paleontological evidence is still very incomplete. The fossil collection is meagre and many specimens have yet to be described in detail. Comparison is made with the Cretaceous of North Western Europe, the nomenclature of which is adopted. No Neocomian or Aptian fossils have been found whereas Albian fossils occur in basal limestones in two localities. No fossils of proved Cenomanian age are known but it is by no means certain that this

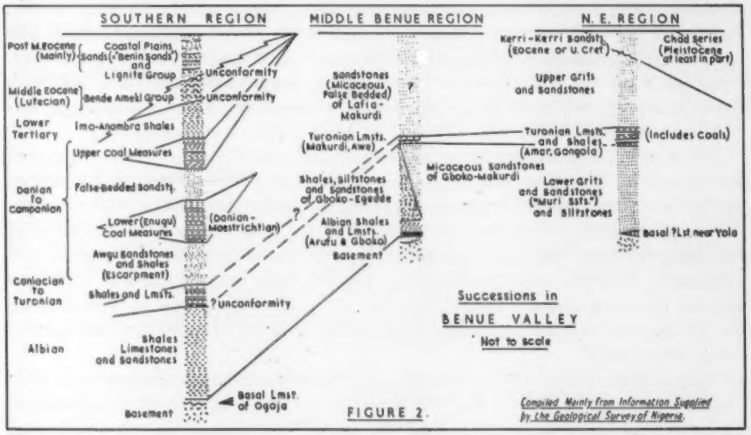

FIGURE 2.

Compiled Mainly from Information Supplied by the Geological Survey of Nigeria.

stage is not represented. It seems that the Nigerian Cretaceous commenced during the Albian and that the major periods of accumulation were during the Albian, Turonian, and post-Turonian.

Precisely where the division between the upper and lower Cretaceous should be made in Nigeria is not yet clear. At present the only horizon that might provide a major marker throughout the field is that at which a series of shales and sandstones with interbedded limestones occurs (Fig. 2). Exposures of beds that may belong to this series occur over almost the whole length of the field: at Igumale, Makurdi, Awe, Amar, Zurak, and at several localities in the Gongola River region. Fossils from these exposures have all been ascribed to the Turonian, mainly lower Turonian (possibly Coniacian at Makurdi). Possible members of this series are all folded except near Igumale where they are merely tilted. Farther southwest, near Awgu, unfolded Coniacian limestone appears to overlie folded Albian beds directly.

Regardless of whether these limestone exposures form a continuous series or not, they are sufficiently near to each other in age to indicate that the underlying folded formations probably constitute a continuous stratigraphical series or group of series. In a field of this size, lacking a sufficient number of dated localities, and in the absence of recognizable and reliable marker horizons, it is obvious that more work is necessary before the stratigraphy can be satisfactorily defined.

In the southern part of the field the lower Cretaceous is represented by a thick series of folded shales of Albian age which passes under tilted sediments at the Awgu escarpment. This series is described by Tattam (9) as being thick, well stratified beds of shales and siltstones with subordinate sandstones. In places the shale and siltstone sequences are modified by intercalations of medium-grained sandstones in beds up to several feet thick. Distributed throughout this region there are dark blue-grey calcareous beds composed of crushed shells in a matrix ranging from almost pure calcite to sand or silt. A grey crystalline limestone is in places associated with the sandstone. The matrix of the sandstones may be calcareous. The folded shale series is intruded and mineralized whereas the overlying Awgu beds are not. Although there is strong circumstantial evidence of a major unconformity here, it has not been proved.

Northeast of Enugu there are a series of shales and fine- to medium-grained sandstones with a zone of interbedded limestones, which separates the folded shales from the Coal Measures of Danian-Maestrichtian age. This intervening formation is lithologically similar to the underlying folded shales; it has been intruded but not mineralized as far as is known; it is tilted and apparently inclined to the northwest. Fossils from Igumale give a Turonian age for this formation. There are beds containing limestone at Makurdi on the Benue that may be Turonian, but it is not known whether the two form a continuous series.

The folded shale series has been followed northwards almost as far as Gboko, and Albian fossils have been collected from it at various localities. In the region between the Egedde Hills and Gboko this formation consists of a thick series of fissile shales (commonly carbonaceous) with thin beds and lenses of limestone underlying a thick series of siltstones intercalated with thin beds of sandstone. The siltstones exhibit considerable variation in different localities: normally soft, massive rocks, in places they become soft poorly sorted greywackes. Intercalated mudstone beds in places occur towards the top of the siltstone series. The interbedded sandstones are commonly micaceous. Grits appear at the base of this formation between Ogoja and Gboko and limestone occurs on the Precambrian contact south of Ogoja. Between Gboko and Makurdi the shale series gives way rapidly to distinctly more arenaceous sediments which have not yet been specifically dated but they underlie the Turonian(?) at Makurdi. The regional structure between the Albian basal limestone north of Gboko and Makurdi is not clearly defined and it is uncertain whether this change is due to overlap, in which case the thickness of the Albian beds is materially reduced, or to a major lateral change

of facies. The fact that both the arenaceous and argillaceous beds underlie limestone horizons of probable Turonian age makes the latter more likely.

From Makurdi to Zurak most of the meager rock exposures are of arenaceous sediments. There are shales, thin limestones, and compact sandstones near Awe which are lithologically similar to the shale formation south of the Benue (Tattam, 11). East of Wase a thick series of shales with fine sandstones, siltstones, and some mudstones underlies coarser sediments. The only described fossils come from Awe, Amar, and Zurak, which are stated to be probably Turonian. The Turonian beds here may be either infolded remnants or an attenuated apron. The arenaceous sediments show some lithological variation in that those between Wase and Zurak are commonly felspathic, in contrast to the micaceous nature of those between Makurdi and Awe. Structurally, there is little evidence of stratigraphic use apart from the fact that these strata are all folded. On general grounds it would seem necessary to postulate a regional inclination towards the northwest to account for the Albian age of the Arufu limestone, the Turonian age of the Awe limestone, and the apparent overlap of still younger sediments farther northwest. Some observers, notably McConnell, regard the main exposures in this region as belonging to Falconer's Muri Sandstone series, which they provisionally assign to the Cenomanian. It seems likely, however, that the lowermost horizons here are stratigraphically continuous with the folded shales of the southwest. Certainly the lower formations comprise a single structural unit throughout, and no definite evidence exists to show that they are not stratigraphically continuous.

In the northeastern region Falconer (1) classified the Cretaceous beds as:

> Upper grits and sandstones,
> Turonian limestones and shales,
> Lower grits and sandstones—Muri Sandstones.

The lower grits and sandstones are well represented in the Gwona district, in the lower Gongola valley, and in the Lamurde Hills where they are well exposed in a major anticline. In the Gwona district they consist of moderately well bedded, but in places cross-bedded, somewhat felspathic siliceous sediments containing many angular to sub-angular grains. Towards the base of the coarse sediments are intercalations of grey calcareous sandstones and unstratified clays, and below them are fine-grained, well stratified sandstones and interbedded clays. This succession is overlain north of Gwona by limestones and shales. The lower grits and sandstones extend southwestward and may be stratigraphically continuous, with facies changes, with the lower horizons in the Wase district. The limestone and shale formation is overlain, possibly unconformably, to the north by the upper grits and sandstones which are post-Turonian in age. These are in turn overlain unconformably by the Kerri Kerri Sandstones, which are late Cretaceous or Eocene. The distribution of these various formations has not yet been defined. Thin coal seams occur in various parts of this region, in the Turonian limestone-shale series, and in the upper grits and sandstones.

Three inliers of the crystalline basement occur in this region. Around the

largest of these the sediments dip quaquaversally at low to moderate angles and there is a suggestion of a pitching anticline at the eastern end. Although it is probable that this and the other inliers represent shallow areas in the Cretaceous basin it is quite possible that this particular inlier owes its position, at least in part, to infolding of the basement into the core of an anticline. Although there appears to be some thinning of the sediments in the vicinity of these inliers the extent of such thinning is probably not large, because the lower sandstones and grits are at least a few and may be several thousand feet thick less than 20 miles to the south.

Sediments of the upper Cretaceous are widely distributed in Nigeria west of Longitude 7°30′E and as an overlap covering most if not all of the northwest flank of the lower Cretaceous in the Benue valley. Further extensive exposures occur in the Gongola valley. These formations, which contain the Coal Measures of Nigeria, have been described as they occur in the southwest by Wilson and Bain (5, 6, 7) and by Falconer (1), Tattam (11), and Brynmor Jones (14) elsewhere.

Estimates of the thicknesses of these formations can only be approximate. Lees [2] estimates a total thickness of 15,000 feet for the Tertiary and the Cretaceous in southern Nigeria. Recent work in this region indicates that this figure may have to be increased. The Albian alone might account for 4,000 to 6,000 feet of this with, perhaps, another 1,500 to 3,000 feet to the top of the Turonian. In the Awgu-Enugu area Tattam [3] states that the sediments overlying the folded shales are known to be at least 3,000 feet thick. Less is known of the thicknesses present at the other end of the field in the Gongola region but it seems probable that the total maximum thickness of sediments here is not less than 10,000 feet and may be appreciably more. The amounts of the original column removed by inter-depositional erosion can only be conjectured. The presence of intrusions and mineralization at Ishiagu at the same elevation, and within a short distance of the contact with the overlying unintruded and unmineralized beds, shows that such erosion must have been material. For the lower Cretaceous this figure may be in the order of 1,500 feet.

Structure.—The structural pattern of the lower Cretaceous presents a single regional unit consisting of a series of parallel or sub-parallel fold systems (Fig. 1). The major systems run more or less parallel to the boundaries of the Cretaceous. Few structures have been traced as individuals for more than 20 miles before becoming dissipated; others appear en echelon giving a stepped pattern. The larger systems generally comprise a single broad regional fold, the limbs of which are commonly puckered by subsidiary folding. The axes are commonly curved, in places strongly. Generally the folding is less intense in the more competent arenaceous strata. The major folds often exhibit axially elongated domes. Many structures display a tendency to pitch at low angles to the southwest.

[2] Discussion on paper by L. C. King: Jour. Geology Soc. London Quart., vol. CVI, pt. 1, 1950.

[3] Unpublished Rept., 1950.

All the major folding must have been accomplished before the Coniacian because beds of this and later age are unfolded. Although there were repetitions of the deformative forces these were fairly near to each other in time and it may be considered that the folding occurred during a single tectonic period. As suggested above it appears that the basement took part in this folding to some degree at least. Parallel structures in the basement flanking the sediments have not been recognized and the extent of this participation is an open question.

Although dip angles are generally moderate to low, areas of high angle dips are not uncommon. The tighter folds may be found close to major anticlinal axes. In one such area in the Egedde Hills two reversals of dip may be seen in shales within 300 to 400 yards across the strike. Some very fine structures exist in the Lamurde Hills in the Gongola region.

The post-Turonian beds have undergone much less deformation and are generally gently flexed or only tilted. The contrast between folded and merely flexed or tilted strata is a useful feature, occasionally the only distinguishing feature between two formations.

Faulting is related to individual rather than regional structures and is not severe anywhere except in parts of the northeast. Minor to moderate normal faulting has taken place from pre-Turonian to Recent times. The principal directions of faulting are northsouth and north-northeast to south-southwest and the most common locus is across the crest of an anticline. In the Gwona area an apparent horst about a mile wide has been observed trending north-south. Slickensiding with very short grooves directed at varying angles near the horizontal, points to recurrent small scale movement in many faults. No thrusting of significance has been observed.

Igneous Intrusions.—There has been considerable intrusive activity, most of it small scale, in many parts of the lower Cretaceous of Nigeria. This activity appears to have reached its climax in late Albian or immediately post-Albian times and to have ceased before the end of the Turonian, since purely intrusive rocks are less plentiful in Turonian sediments and absent from the Coal Measures and higher horizons. Volcanic activity on the other hand is known to have occurred until Recent times.

Intrusive rocks are widely distributed from Ishiagu almost as far as Zurak, a distance of 310 miles. Within this belt there are many more occurrences known in the southwestern than in the northeastern half. Northeast of Zurak few intrusives have been recorded, but this region has been less well examined. Several small concentrations of intrusive rocks are to be found between Ishiagu and Aghila Hill, the more notable localities being: Ishiagu, Abakaliki, Lefin, the Egedde Hills, and the Aghila area. The best, from the standpoint of variety and range of types, is the Aghila area. Here there is a most interesting group of small to medium sized intrusions consisting of all the igneous types known in the field. Northeastwards of this point intrusions are less common. Careful examination of almost any area, however, generally discloses some igneous rocks that either do not outcrop or are inconspicuously exposed. Doubtless many more occurrences remain to be found.

This intrusive suite is intermediate to basic in character and all its members are probably genetically inter-related. Although there is a fairly wide range of types the variations are due more to diverse cooling conditions than to differences in composition. Hypabyssal and plutonic types of similar chemical or mineralogic composition are common. Other variations are probably due to magmatic differentiation. The Aghila complex exhibits a concentric arrangement of types, becoming more basic from the center outwards. The types represented range from syenites to gabbros with several corresponding hypabyssal equivalents. Perhaps the most common, certainly in the southwest, is an albitized dolerite. A few of the coarser types are porphyritic with phenocrysts of felspar. Lamprophyric rocks with hornblende phenocrysts are not uncommon. Ophitic and sub-ophitic textures are seen in many of the doleritic rocks. Porphyries are scarce.

The plagioclases in practically all these rocks fall within the oligoclase-labradorite range when not albitized. Orthoclase and, less commonly, perthite occur in some coarser dioritic types. The mafic minerals are chiefly augite and hornblende and secondary minerals derived from them, with less common biotite and aegirine. Quartz occurs rarely and then sparingly. Iron and titanium oxides are common and may be abundant. Chlorite, calcite, and sericite are among the more common secondary minerals. In the doleritic rocks the plagioclase may be albitized and the pyroxene uralitized. As Tattam [4] points out, this is characteristic of dolerites intruded into folded sediments, particularly when sedimentation, folding, and intrusion are not widely separated in time.

There is a marked association between the intrusions and the sedimentary structures. Concentrations of intrusive rocks favor the better developed anticlines and more than one important igneous center is located with a domed structure.

The emplacement of these intrusions was for the most part quiet although certain local phases must have been accomplished violently. Coeval structural deformation of the invaded sediments is generally slight and is rarely of more than local importance. Even in the more intensively intruded Aghila area, the structural effects of intrusion are not regionally significant. Metamorphism of the sedimentary host rocks is weak and very local. Near an intrusive contact there is commonly some induration which, however, disappears rapidly away from the contact. This induration has produced flagstones in some localities.

These intrusions have adopted many forms from sills and dikes to bosses up to a mile or two in diameter. One apparent laccolith has been observed in the Aghila area. The exact habit of many occurrences has not been determined, but it would appear that the commonest forms are dikes or sills (a proportion of which are slightly discordant) and small to medium sized irregular ellipsoidal masses which favor a roughly east-west elongation. In the Aghila area dolerite and trachyte dikes show distinct directional trends, the former favoring a north-northwesterly and the latter a northeasterly strike.

Trachytic sills, and possibly lavas, exhibiting flow structure and

[4] Unpublished Rept., 1950.

amygdaloidal greenstones have been observed in the Aghïa complex. Breccias occur at Abakaliki, Lefin, and near Tunga. The last two of these may be agglomerates but the first certainly does not belong to the latter extrusive period. The origin of these clastic rocks presents a problem of more than academic interest since all three occur with lead-zinc lodes. The existing evidence is conflicting and a completely satisfactory explanation of their origin has not been found. In the Abakaliki case Tattam [5] considers that they are probably intrusion breccias. In the other two cases insufficient evidence exists on which to base an hypothesis. In the last case the breccia interrupts a lode and contains fragments of ore in circumstances that cannot be explained by fault brecciation.

It is open to question whether the trachytes and phonolites are related to the intrusive or the volcanic suite, or neither. It is assumed that the trachytes and phonolites are more or less contemporaneous because of their petrological affinity and similar habit, but this is not established. In the Aghila area they occur associated with dioritic rocks that are almost certainly older; elsewhere they are only known to occur alone. Similar trachytic rocks are common in the Cameroons where they are among the earliest representatives of the volcanism that lasted from late Cretaceous to Recent times. In the lower Cretaceous field the trachytes and phonolites occur mainly as isolated necks, in places forming conspicuous hills, scattered from Aghila Hill to the Gongola. Trachytic rocks other than necks are only known near Aghila Hill in this field, although petrologically similar lavas, tuffs, and dikes are plentiful in hilly Precambrian parts of the Cameroons. There, erosion has been more active and extrusive remnants are less likely to have survived if the trachytes of both regions are contemporaneous. Trachytes and phonolites are not known to intrude the Turonian limestone or higher horizons and would appear to come nearer in time to the older intrusives, and yet they show a closer petrological affinity to the later olivine basalts.

Extrusive Rocks.—Volcanic activity was widespread in many parts of eastern Nigeria from the late Cretaceous to Recent times. The earlier extrusives of this suite are acid to intermediate in character and were followed by basic effusions. In the lead-zinc field, basaltic lavas and a few pyroclastics occur in a number of localities. The distribution of the basic extrusives is known to coincide with that of the intrusives in only two localities, viz., the Egedde Hills and the Aghila area; otherwise they are found separately. From southwest to northeast the more important basaltic occurrences are situated as follows:

1. South of Obubra on the Cross River.
2. Egedde Hills and Lefin area.
3. Northeast of Ogoja.
4. Aghila area.
5. South of Makurdi.
6. Arufu area.
7. Awe area.
8. Widespread in the Gongola region.

[5] Unpublished Rept., 1950.

The lavas, for the most part, are typical olivine basalts that are rarely vesicular or amygdaloidal. Sills occur in a number of localities and one laccolith has been recorded south of Makurdi, but the general habit is small cones and lava sheets that seldom exceed a few square miles in extent. Apparent pillow structure is seen in one instance, and minor occurrences of tuffs and agglomerates are found in the Aghila area. Basic tuffs have also been seen in the northeastern part of the field. These extrusives emanated from a number of small volcanoes, many of which can still be recognized. Although well preserved and obviously very recent cones exist in other parts of Nigeria, none quite as young occur within the lead-zinc field. Some of the cones have had most of their surrounding lavas removed by erosion; others still have fairly extensive, though partly dissected sheets, remaining. No intermediate or acid extrusives have been seen in the field except in the Aghila area; the phonolite and trachyte necks may represent old volcanic plugs.

These basic volcanics bear many points of resemblance to the basalts that occur in other parts of Nigeria and there is little doubt that they belong to the later stages of this widely distributed suite. There is little reason to suppose that they bear any direct relationship to the earlier intrusives. The basic volcanism probably did not commence until well after the close of the Cretaceous.

Brine Springs.—Dilute brine springs are fairly common throughout the field, occurring in scattered groups. The springs are mostly little more than small wells or seepages, as the flow is very small in all cases. All the springs are cold. No salt beds or deposits have been observed in the sediments. The salt content appears to be derived by the leaching of disseminated alkaline salts. Brine springs emanate from both coarse and fine sediments and show no direct association with the igneous rocks, although they are more common near areas of mineralization. Many of them are utilized by the local inhabitants as sources of salt, which is obtained by evaporation. Three samples of brine from the south-central part of the field proved to contain sodium and potassium chlorides. A sample from farther southwest contained a mixture of sodium and magnesium sulphates with a trace of potassium sulphate.

Calcareous Springs.—Only one calcareous spring has actually been observed; it is near the small village of Diji in the Gwona district. Here, there is a slow up-welling of lime-charged water in several places on and around a conspicuous knoll of calcareous sinter. A few other small accumulations of calcareous sinter occur in this locality without springs. These and other similar occurrences in the northern part of the field indicate that such springs were more active in the past.

Rock Weathering.—Present erosion is active enough to remove the weathered skin of rock outcrops as fast as it forms in only a few parts of the field. Consequently, few outcrops are free from decomposition, and many are more or less completely rotted. The argillaceous sediments and igneous rocks have suffered deeper and more extensive weathering than the coarser siliceous sediments. The depth to which weathering has penetrated varies considerably. To date there is little underground evidence on this question but it is probable that there are few parts of the field where the average depth of more or less

complete weathering is less than 50 feet below the surface. Partially decomposed rocks and narrower zones of more complete weathering occur to appreciably greater depths.

The matrix of the coarser sediments has been weathered and loosened and may be partially removed, thus softening the surface layer of the rock without destroying either its fabric or structure. Where the matrix of these rocks is calcareous, the effects of weathering are more pronounced and secondary calcite may develop. In arkoses and felspathic sandstones, the felspars are rapidly reduced to clay, materially weakening the rock but seldom destroying its fabric. Color changes due to weathering are not striking: outcrops generally remain gray but sub-outcrops and deeper weathered zones are bleached to pale gray or white. In the finer sandstones, the effects of weathering are more pronounced, particularly in impure varieties. In extreme cases the rock structures may have been altered by the partial destruction or masking of the bedding planes. Bleaching to pale gray, beige, or white is the common color change. Limonite coating occurs and in places advanced to the point of ferruginization.

All the argillaceous sediments are affected by weathering accompanied by striking changes to paler colors, even to pastel shades. This bleaching may be due to oxidation of the carbonaceous content. The cohesion of the rock is weakened and there may be some increase in volume in a number of cases. The rock structure is not generally obliterated; it may even be accentuated. A few of the less competent mudstones appear to have been displaced by squeezing in the weathered zone, and can now be seen as small injections into more competent strata.

The igneous rocks have been attacked in varying degree by weathering. An exception is a hard dense basalt, occurring in a few localities, which is often found quite fresh. The depth of weathering is very variable: it is generally in excess of 10 feet but may be only skin deep. Most of the mineral constituents are altered, many completely. In the finer-grained varieties this alteration commonly masks the original composition; in coarser-grained rocks the texture is generally preserved. Color changes are not consistent; a dull dark green is most common but many bleached examples exist and some dark brown colors due to secondary iron are seen.

Lateritization.—Lateritization is a common feature in this field, particularly in association with the finer sediments and igneous rocks. Its expression is more commonly that of a surface or near-surface layer of compact red-brown ferruginized rubbly clay rather than a rock-hard laterite. Both types however effectually mask the underlying geology since none of the rock structure is reflected in the lateritic overburden. Attempts have been made to determine the nature of the underlying rock from the character and composition of the lateritic layer but the results have been only partly successful.

Lateritization is most common in the central part of the field. In the southwest, where erosion has been rather more active recently, the products of lateritization are less widespread. Lateritic clays exist but are not as common as in other parts of the field; hard laterite is largely confined to areas of the younger beds to the west. In the northeast, where coarse sediments prevail

and the relief is greater, lateritization is confined largely to the flatter areas underlain by basalt. In the central region, lateritization is widespread. There are a number of extensive hard laterite sheets, notably on and near the Benue Aiya watershed. The hard cellular laterite occurs at or near the surface and is rarely thicker than 3 feet. It is generally underlain by lateritic clay. Elsewhere lateritic clays are common. They may occur from the subcrop to the surface, but may be overlain by a thin layer of soil. They consist of compact red, brown, and yellowish clays that contain hard ferruginous pellets near the upper surface. These pellets may form the major part of the upper layer, giving rise to a semi-consolidated rubble bed that lacks only cementation to produce hard laterite. There is little visible variation in the lateritic clays overlying different types of finer sediments; those overlying sandstones are marked by their sand content.

MINERAL DEPOSITS.

The Ore-Bearing Zones and Their Formation.—The lead-zinc deposits of this field, with one minor exception, are all fracture filling veins. The mineralized fractures form part of fractured or sheeted zones. Individual zones exhibit a fairly simple pattern of closely jointed ground in which one or more better developed fractures may occur. The width of the zones varies from a few feet to 50 feet or more averaging, perhaps, 20 feet in better developed cases. Few zones have been accurately delimited in strike beyond ore lenses, but several are known to exceed a mile in length. The stronger fractures are generally straight, although curved examples exist. In strong zones two or more fractures commonly parallel each other, one of which is always more strongly developed; as the strength of one diminishes, the role of major fracture is assumed by another so that the zone is seldom without one strong fracture at any section. The culmination of some zones appears to be a series of divergent fractures. Some of the fractures are also minor faults along which repeated small scale movement has taken place, much of it more or less horizontally. Brecciation has occurred at places along a few of these faults.

Spur fractures occur but are not common. They normally leave the zone at angles of 15° to 30° in a left-handed direction and are seldom well developed or persistent for more than a few hundred feet. Diagonal or cross fracturing within the zones is weak and unimportant; cross faulting is rare. The fracture zones are not appreciably sheared and there is little evidence of crushing. The differences in dip of the strata to be seen on opposite sides of some zones indicate, however, that shearing forces contributed to their formation. Parallel zones may exist within short distances of each other. In these cases the less well developed zone is generally weak and contains only minor mineralization. In the prospects west of Ishiagu there is one case where five more or less parallel and equally developed veins occur within a belt 450 feet wide.

There are two main sets of fracture zones that probably were developed at different periods, as will be discussed later. The first set, in which the chief

ore veins occur, strikes within 20° of north, the most common direction being slightly west of north. The second set strikes between northwest and west.

Fracture zones of the first set are nearly all associated with anticlinal structures, which they cross more or less at right angles. Most of these zones dip steeply but few, if any, dip vertically. Most of the dips in one locality are in the same direction, although the angles of dip may vary. The flattest recorded dip is 45° (Zurak). The fracture zones seldom, if ever, occur alone; groups in which individual zones are situated up to three miles apart are common. These zones are thought to have formed first, because they carry the earliest gangue and ore minerals, and contain later minerals only under circumstances suggesting that they were subsequently reopened. Generally zones of the second set are less well developed; they may consist of only a single fracture accompanied by weak jointing. They are more numerous, but less faulted than those of the first type. Vertical and steep dips appear to be the rule. In the Wase area they tend to occur in scattered groups, in places with one or more zones of the first type. Elsewhere, they seem to occur haphazardly near anticlinal axes, and in a few places intersect north-south zones.

The mechanism and timing of the formation of these fracture zones must remain largely conjectural at present. The following is offered as a brief and tentative analysis.

The stepped pattern of the folding, the domed structures, and the transverse jointing, indicate that the deformation was caused by compression that included an element of rotational stress in the horizontal plane. The initial rupturing took the form of jointing in two directions inclined at 45° to 80° to each other, the major direction being more or less at right angles to the fold axes, i.e., somewhat west of north. This jointing developed in rather indefinite but fairly narrow belts that later acquired better definition as the intensity of jointing increased. Subsequently, fracturing and then faulting developed in some of the north-south belts. The first phase of mineralization, the introduction of siderite, took place at this stage. The siderite veins were reopened from time to time giving access first to sphalerite, and then to galena. Recurrent small-scale longitudinal faulting accompanied and followed these phases of the mineralization. Continued or renewed stresses, acting rather more obliquely to the existing structures, caused further rupturing to occur in the hitherto minor jointing direction. The growth of this set of fracture zones did not reach the stage of development of the first. The original fractures were not extensively reopened during the evolution of the second set. When the later siliceous phase of the mineralization arrived, the principal passages available were the fractures of the second set. These were then mineralized, together with the re-mineralization of the accessible portions of the north-south veins.

Vein Characteristics.—The lead-zinc veins of this field are the result of fracture filling. True replacement is insignificant except, possibly, in a few limited cases. The only veins that traverse limestone are those at Arufu and Akwana, and even here replacement is not important. There is a strong similarity in the mineral assemblage and other characteristics in veins of the same type throughout the field.

All the lodes are markedly lenticular in habit. In the earlier (north-south) veins there are generally two or more lenses repeated along the strike, in places slightly off-set. The later veins may consist of a single lens, although repeated lenses are also common. In general, the veins are narrow (less than 8 feet) but locally they may swell to appreciably greater widths; lenses are characterized by pinches and swells. The vein material contains angular fragments of included wall rock. In lodes with siderite gangue the sulphide content varies considerably in quantity. Either sphalerite or galena is nearly always dominant, but one may change abruptly to the other, either laterally or vertically. Beyond the ends of lenses, the veins consist of one or more thin stringers of gangue with few sulphides.

Although most of the primary vein material is more or less free from open spaces vugs are plentiful in parts of some veins. They are mostly small, narrow, longitudinal openings, that occur chiefly where there is a high proportion of quartz gangue; many are lined with quartz crystals. Marcasite is often found where vugs are plentiful.

The outcrops of these veins have been extensively excavated in the past and undisturbed outcrops are rare. This is particularly true of the siderite-rich veins and the author does not know of a single completely undisturbed outcrop of any size of this type. Honey-combed gossans, that may contain secondary lead minerals, are the usual surface expression of siderite-bearing lenses. These form low eminences that are rarely prominent. The outcrop between lenses is generally quite inconspicuous. Veins with quartz gangue have been little disturbed and are marked by lenticular quartz outcrops.

There are two large outcrops of gossan, one at Ugulangu, between Ishiagu and Ameka, and one at Rikaya 15 miles east of Wase. Neither has been sufficiently probed to permit satisfactory examination as yet. Both form low hills, Ugulangu rising over 100 feet above the surrounding ground. Here, the gossan is wide and is composed of limonite and silica and some hematite. At Rikaya two small groups of low hills are composed of fine sandstone with veins, lenses, and small masses of siliceous and ferruginous gossan. These gossans are barren, or carry only low lead values. In the primary state they are probably composed of siderite and quartz.

In the coarser sandstone country of the northeast the vein characteristics are somewhat different. Siderite is uncommon and the only gangue of consequence is quartz, and much of this appears to be the result of silicification of the sandstone walls. Here, narrow silicified veins carrying erratic stringers, small knots, and disseminations of galena run in a north-south direction. Numerous veins of this type occur in the Gwona district with a little copper. Zinc is almost entirely absent here but occurs farther southeast.

The character of the wall rocks appears to have an important bearing on the size and nature of the veins. Tattam [6] considers that the type of country rock is a major factor in determining the strength of mineralization. Certainly all the more promising deposits occur in the finer sediments. Since replacement is not an important mode of mineralization, the control ex-

[6] Unpublished Rept., 1950.

ercised on the fracturing by the nature of the strata and, possibly, the dispersion of the mineralizers in the more porous rocks appear to be the governing factors.

Mineralization.—The sequence of mineralization has been tentatively established as:

Earliest:	1.	Siderite + some quartz,
	2.	Sphalerite (massive),
	3.	Galena (massive),
	4.	Calcite (minor),
	5.	Chalcopyrite (minor),
Latest:	6.	Quartz, marcasite, and disseminated galena.

Barite is an important gangue mineral in a few veins; fluorite occurs abundantly in two veins; and one case of witherite is known. These unusual gangue minerals are probably related to the latest quartz phase. Enargite has been identified in two veins and tetrahedrite reported at Zurak. These minerals are probably associates of chalcopyrite. Orpiment is reported as a rare mineral at Zurak by Mackay (12).

The siderite is a light cream color that changes rapidly to dark brown on exposure to the air. It is generally, if not always, manganiferrous. Some quartz commonly accompanies the siderite as small blobs and irregular lenses or veinlets, rarely massive. The siderite was introduced in bulk in most cases and its emplacement must have been completed fairly rapidly because of: (a) its coarse sub-individual crystallization; and (b) its content of quite large angular wall rock fragments. The latter feature is particularly noticeable near the edges but wall rock fragments may occur anywhere in the vein. Replacement of the wall rocks by siderite is unimportant; siderite has only invaded the minor fractures and joint planes in the walls as thin stringers and small lenses. The vein walls are nearly always slightly irregular frozen contacts. Post-siderite fracturing and sometimes longitudinal faulting is common but these breaks seldom coincide with the vein walls.

The sphalerite is mostly dark brown, opaque, coarse, well laminated, but not well crystallized. Very occasionally a translucent resinous variety is seen. It is mostly massive and occurs as: (a) irregular aggregates up to a foot or more in size; (b) massive lenticular veins; and (c) short irregular veinlets traversing siderite. In places it forms the bulk of the vein matter. The sphalerite may be partly idiomorphic, and is remarkably free from inclusions and admixtures with other minerals. A lump of undressed sphalerite about ¼ lb. in weight with very little visible gangue from near Ishiagu assayed 64.4% Zn. Although composite lead and zinc ore is common, sphalerite and galena generally form separate veins or aggregates, and the portions of lodes rich in zinc as a rule contain only small amounts of galena and are seldom contaminated with other ore minerals. Parallel or alternating bands of sphalerite and galena occur.

The earlier and more important generation of galena is lead-gray, massive, and usually has a highly perfect cubical cleavage. Some fibrous galena is

found scattered in parts of most lodes bearing the massive mineral. Cubo-octahedral galena occurs in the small Ijegu prospect where the mineralization is along narrow cleavage planes in shales. Galena occurs as veins, lenses, stringers, or lumps up to many feet in size and in places forms practically the entire vein filling. The veins or stringers generally follow the direction of the main vein but may also cross it obliquely. Individual veins are rarely persistent. Galena has been observed traversing earlier sphalerite. The boundaries of the galena aggregates are mostly frozen, but narrow open fractures following one wall of a galena vein do occur. Disseminated galena is not common in this type of ore.

The silver content of the galena ranges from one to ten ounces per ton of crude galena over most of the field. High silver values, although not rare, appear to be confined to certain lodes or ore-shoots. Galena concentrates shipped from the Zurak Mine from 1935 to 1937 consistently averaged 120 ounces of silver per ton. Higher silver assays have been recorded but they are from isolated samples and would not appear to be representative, even of small ore bodies, except at Arufu where native silver occurs. Bain [7] records sphalerite carrying 22 oz. of silver per ton from Zurak. Very small quantities of gold and cadmium have been determined in galena; bismuth has not been detected, even in the cubo-octahedral galena from Ijegu. A little chalcopyrite is seen with galena in some veins; sphalerite and galena are not often intimately mixed; otherwise the galena is free from visible admixture with other sulphides in the primary state.

Calcite is not a common gangue mineral as a rule, yet it is moderately abundant in and near some veins. It generally occurs as narrow veins and veinlets or as small irregular lenses, in places striking obliquely to the main vein. It is also seen as narrow, short, veins and veinlets traversing the wall rocks. The calcite itself is not mineralized. Secondary calcite occurs in the oxidized zone of many veins.

Chalcopyrite occurs as a minor mineral in many veins in small knots with galena or quartz, rarely with sphalerite. The conspicuous secondary malachite and azurite tend to give a false impression of the abundance of copper minerals in the outcrop section of some veins. Enargite has been seen only north of Tunga where, in one case, weak enargite mineralization follows the bedding plane of fine calcareous sandstone. Farther south a very little enargite has been seen in a small quartz vein. Tetrahedrite has been recorded as a rare mineral at Zurak by Mackay (12).

The final siliceous phase of the mineralization is thought to have occurred an appreciable time later. The principal gangue of this phase is quartz. Some veins between the Egedde Hills and Gboko have an admixture of barite. Galena is the most common and generally the only sulphide present. It is widely but erratically distributed in the quartz veins and lenses, in some places disseminated in cubes, and in others as small knots or discontinuous veinlets of sulphide. A little chalcopyrite may belong to this phase. The quartz is abundant and generally massive; most of it is white, but sugary and

[7] Unpublished Rept., 1935.

massive bluish varieties occur; it is seldom banded and then only crudely. Crystals of quartz line the walls of fractures and vugs.

In the south-central part of the field where barite occurs, it may be the principal gangue mineral, but it is generally subsidiary to quartz. In cases where barite and quartz occur together, any galena there may be shows a marked affinity for the barite. A few veinlets of witherite occur a few miles north of Aghila Hill.

Marcasite is associated with many of the quartz bodies and may be locally abundant. Generally, however, it is sparsely distributed. It occurs as spongy masses or in mammillary forms and may assume vein form; it also occurs in the wall rocks as tiny veinlets and lenses. Bain [8a] describes marcasite attaining the exceptional thickness of 40 feet at one point in the Ameka lode. The marcasite decomposes rapidly on exposure, and native sulphur is often seen on the freshly exposed mineral. In the massive form it commonly shows concentric banding. Mackay (12) has observed marcasite coated with galena and sphalerite at Ameka and Bain [8b] describes pockets of galena enclosed by marcasite from the same lode.

There are two veins, at Arufu and Akwana, in which fluorite forms an important part of the gangue. They traverse limestone and McConnell [9] considers that this accounts for the presence of fluorite. Native silver has also been found at Arufu where a considerable pocket was discovered and worked out in 1885.

Ore Genesis.—Evidence bearing on the question of ore genesis can be summarized as follows:

1. The early intrusives are unmineralized by sulphides (except for a little pyrite) yet dolerites and porphyries of this suite are traversed by ore-bearing veins.
2. The extensive albitization of many of the dolerites suggests that magmatic emanations were active shortly after their emplacement.
3. Mineralization and intrusions both favor anticlinal structures.
4. Dioritic intrusives are common, though not in all places, in close association with the lead-zinc veins.
5. Mineralization occurs west of Ishiagu less than 4 miles from and at the same elevation as the base of unmineralized and unintruded sediments of Coniacian (immediately post-Turonian) age.
6. Mineralization did not reach as high in the stratigraphic column as the basic extrusive rocks.

From the above it will be seen that mineralization may have taken place at any stage from the late Albian to the end of the Turonian. More definite timing must be conjectural but the extensive albitization of the dolerites suggests that mineralization may well have followed shortly after the emplacement of these rocks. As they are the earliest intrusives known in the field this would place the mineralization at a fairly early stage. The common asso-

[8a, 8b] Unpublished Rept.
[9] Unpublished Rept., 1949.

ciation of dioritic rocks and mineralization suggests a genetic relationship between the two. The mineralogy and other known characteristics of the more important veins in this field correspond well with those of other well known galena-sphalerite-siderite associations elsewhere. Tattam [10] considers the best analogue to the Nigerian field to be the Rhenish Schiefergebirge. Here, and in other similar fields, the mineralization is generally regarded as being of magmatic hydrothermal origin and there are not any cogent reasons to believe that the mineralization in the Nigeria field differs in this respect.

The occurrence of ore in folded Albian shales at the same elevation and close to unfolded and unmineralized Coniacian beds at Ishiagu is evidence of the removal of an unknown thickness of the Albian and, probably, of the Turonian also, from a wide area of this part of the field before the post-Turonian sedimentation. It is not known how much of this erosion took place after the mineralization but some at least was post-mineralization. Subsequent erosion removed a further unknown thickness of the Albian to bring the land to its present level. In the Egedde Hills, residual hills of Albian sediments rise almost a 1,000 feet above the surrounding country, indicating that the total denudation of the Albian in this area was considerable. It is fairly certain therefore that a substantial thickness of cover has been removed to expose the present outcrop levels of the veins in this region. High residual hills of the older sediments in the northeastern part of the field point to the same conclusion. Consequently, it may be inferred with some degree of assurance that mineralization took place an appreciable distance beneath the existing surface. The massive nature of the ore and gangue minerals, the dark opaque sphalerite, and the general characteristics of the mineral assemblage indicate formation at a medium temperature. (The latest phase of the mineralization, which included the marcasite, was probably deposited at a somewhat lower temperature.) It is concluded that these veins were formed under mesothermal conditions.

Vein Weathering.—The lead-zinc veins are extensively oxidized above the water table. Alteration in some places is so complete that none of the original vein material remains in its primary condition. Veins with siderite gangue are much more readily attacked than those with quartz. Weathering causes the following changes in the minerals found in these veins:

1. Siderite = Limonite, hematite, various dark oxides, + pyrolusite.
2. Sphalerite = Smithsonite (rare), mainly removed by solution.
3. Galena = Cerussite and anglesite (common), pyromorphite and lead oxides.
4. Chalcopyrite = Malachite and azurite.
5. Marcasite = Iron oxides.

The siderite is almost completely altered in the uppermost sections of the veins. Its secondary products have a very marked masking effect on the oxidized portions of the veins and it is difficult to observe other minerals in the assemblage unless they are plentiful or massive. This process also de-

[10] Unpublished Rept., 1950.

stroys most of the primary vein structure. The resultant weathered vein is an amorphous mass of black and brown iron oxides with variable amounts of finely powdered pyrolusite and, in a few places, some very fine micaceous hematite. Where massive galena occurred in the primary vein, irregular residual lumps appear in the oxidized portion. Zinc minerals are extremely rare in the well weathered portions of veins. Secondary copper minerals are occasionally seen. The transition from completely weathered to largely unweathered as the vein is followed downward is quite abrupt and may occur above the permanent water table.

The sphalerite in the completely oxidized zone has been largely removed by leaching, leaving little detectable secondary mineral. Smithsonite occurs rarely. At the zone of passage from completely oxidized to largely unweathered ore, the sphalerite is indistinguishable from the primary mineral further down.

The galena is less extensively altered. In the oxidized zone it is quite common, and is always coated with powdery anglesite. None of the galena in the oxidized zone bears any sign of secondary origin. Cerussite, a common secondary product occurring in the drusy portions of the veins, is generally colorless to light brown (in places gray or black) and well crystallized. Secondary lead minerals occur scattered through many parts of the oxidized zone and do not favor any particular horizon or setting. Most of them would appear to have formed close to the original position of the galena from which they were derived. Cellular secondary vein material with numerous cubical casts points to leaching of the lead, but it seems probable that most of the redeposition took place nearby and that the net impoverishment or enrichment is of a low order.

The extent to which secondary action has re-distributed the lead and zinc in the upper portions of these veins is important at the present stage of investigation. While there is no doubt that a large proportion of any zinc originally present in the oxidized zone has been removed, the behavior of the lead is open to question. Mackay (12) believes that migration of the ore minerals accounted for the increase in the Zn:Pb ratio from surface to a depth of 280 feet at Zurak. Since this was written, diamond drilling has indicated that the Zn:Pb ratio may also decrease with depth over a similar limited range. There is no direct evidence that any supergene sulphide enrichment has taken place. The abundance of carbonate and the general scarcity of iron sulphide in these veins and the fact that such enrichment is rare in lead-zinc ores, are arguments against this hypothesis. The author prefers to regard these changes from lead-rich to zinc-rich ore as being entirely due to primary causes, the sphalerite and galena having been introduced in bulk to different portions of the same lode at different periods, the apparent selectivity within short ranges (horizontally or vertically) arising from the fractures available to each at the time.

The primary copper ores alter to brightly colored malachite and, less commonly, azurite. In places, these minerals are beautifully crystallized in very fine forms. They are scattered in small clusters suggesting that they, too, have not migrated far from the positions of the primary chalcopyrite.

Veins in which quartz is the predominant gangue are much less affected by weathering. Even so, the original sulphides have suffered appreciable alteration, particularly where the quartz is less massive.

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X-RAY STUDY OF COAL FROM LOGAN COUNTY, WEST VIRGINIA, AND A DISCUSSION OF THE STRUCTURE OF COAL.

ROBERT S. YOUNG AND DAVID S. ROBERTSON

ABSTRACT.

Seventy-four surface, drill core, and underground samples representative of the eight industrial seams within the limits of Logan County, West Virginia, were studied by X-ray methods. The coals are of Kanawha (Upper Pottsville) and Allegheny age. Samples, for the most part, were composite.

The powder X-ray technique was utilized with a number of variations in specimen preparation. Copper and iron radiation were used with 114.59 mm cameras employing the Straumanis technique of film calibration.

Extraneous crystalline impurities identified through X-ray means alone were kaolinite, quartz, pyrite, calcite, and dolomite in order of decreasing occurrence. Of these mineral impurities, only kaolinite appears to occur with any preferred orientation.

Information on the structure of coal derived from the study of these high-volatile bituminous coals was compared with the information obtained from specimens of Pennsylvania anthracite, Cretaceous low rank bituminous, and Pennsylvanian semi-bituminous. Results obtained suggest that the "free" carbon in coal is in the form of graphitic crystallites, as indicated by diffuse halos in the region of the prominent graphite diffraction lines. Volatile matter and moisture in the coal appear as secondary scattering on the film. Slight shifts of the {002} halo indicate a definite change of the graphite crystallite size with coal rank change.

Previous literature on the X-ray study of coal is reviewed and discussed.

Advantages and disadvantages of the X-ray method are compared with other methods of coal analysis, from the standpoint of structural determinations.

INTRODUCTION.

Coal Samples.—The greater part of the coal samples used in this study were taken in Logan County, West Virginia, and are of Pennsylvanian age. Sampling was restricted to seams of present or prospective industrial value. The seams sampled, from oldest to youngest, were: No. 2 Gas (Eagle), Alma-Draper, Cedar Grove, Williamson, Chilton, Winifrede, Coalburg, and No. 5 Block. The seams No. 2 Gas through the Coalburg are of Kanawha (Upper Pottsville) age and the No. 5 Block is of Allegheny age. All samples were composite; where feasible the samples were two inch by two inch channels, otherwise they were one inch by one inch channels. There was no prerequisite to sampling other than that they be at least one thousand feet apart laterally. This was designed to show horizontal variations in impurity content. All of the industrial coals of Logan County are classified as high-volatile bi-

tuminous coals, the volatile content varying between 31 percent and 40 percent. Taking "free coal," the ash content varies from 2½ percent to 9½ percent.

Specimen Preparation.—As the original coal samples were composite, it was desired that the actual X-ray specimen also represent all of the components of the seam. The mine samples were taken and reduced in quantity in the usual mine sampling manner. The final sample, weighing approximately three (3) pounds, was ground to forty (40) mesh and further reduced in quantity to four (4) ounces. The final four ounces were thoroughly mixed. During this procedure, all possible precautions were exercised to prevent contamination of the individual samples, either by foreign matter or other samples. A small portion of the four ounces was ground in a mortar and pestle to about the consistency of ordinary face powder (240 mesh). Following directions accompanying the diffraction unit, the coal powder was coated on a pyrex glass fiber with household cement by first rolling the fiber in the cement and then in the coal powder. However, it was found shortly that the pyrex glass gave a diffraction pattern very similar to that of coal and therefore could not satisfactorily be used. After several trials with other types of holders, it was determined that the pattern of lead glass tubing was not objectionable. Tubing was selected because it cut down on the volume of lead glass present in the holder, and therefore reduced the amount of absorption of the X-rays. Further experimentation revealed that the diffraction pattern of the household cement was also objectionable, as were the patterns of nail polish, rubber cement, casein glue, petroleum jelly, fir balsam, and shellac. The pattern of "water glass," a commercial colloidal silicate, was found to be satisfactory and all subsequent powder samples of coal were run on a lead glass fiber with the water glass acting as an adhesive. Even with these precautions, one could not be sure that the diffraction pattern given was the true coal pattern, free from the additive or suppressive effects of the fiber and bond. For this reason, small slivers of solid coal were run in place of, or along with, the powder specimens. The use of the solid coal specimens proved that the patterns received from the powder patterns were true coal patterns, but the patterns from the solid specimens were much more intense. The solid specimens greatly increased the mass of the coal present in the actual sample, thus insuring a true and definite coal pattern. It also removed the possibility of contamination of the sample with "rock dust" from the mines. The diffraction lines received from solid coal specimens are from crystalline impurities actually enclosed in the coal. At the same time, however, use of the solid coal specimens made the sampling selective rather than composite. The solid specimens were run non-rotating and the completeness of the impurity lines in these samples indicates the finely divided nature of the crystalline particles (Fig. 1A). No special preparation was given the solid specimens, other than to crush the coal and select a small, elongate chip.

X-Ray Theory.—The X-ray method used in this study of coals is termed the "Powder Method." The general procedure and basic equipment were developed by Debye and Scherrer in Europe and by Hull in the United States. The powder method, which is most convenient and best suited for the study

of microcrystalline and polycrystalline substances, may prove to be well suited for the study of "amorphous" substances. If crystalline, the material to be studied must be naturally made up of numerous small crystals oriented at random or it must be reduced to this state through grinding. This random orientation is necessary so that, when a beam of essentially monochromatic X-radiation passes through the powder, there will be a sufficient number of crystalline particles so oriented that a given reflection {hkl} is possible. The crystals or crystalline fragments that produce a given {hkl} reflection may

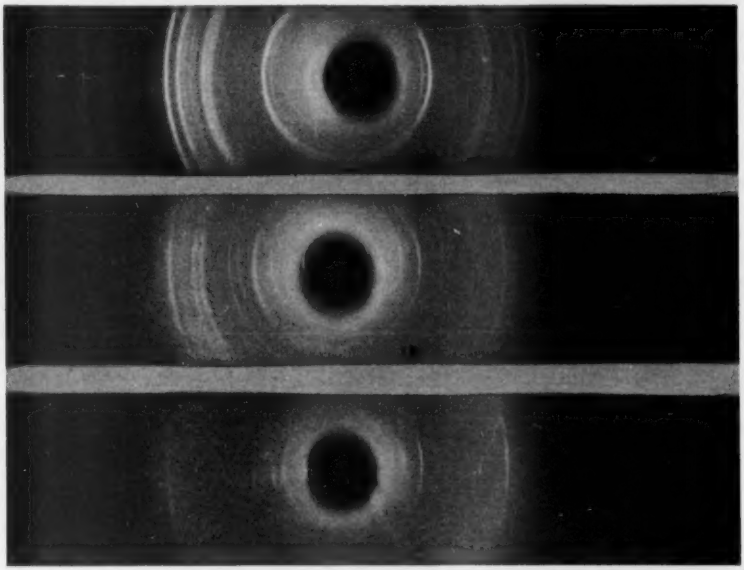

FIG. 1. A. Diffraction pattern of Logan County sample B-12. Note purity and completeness of kaolinite pattern. Fe radiation, no filter. B. Logan County sample no. 691. Note position of off-center, low-angle line *inside* of scattering. Specimen not normal to beam. C. Logan County sample no. 691. Specimen normal to beam.

be oriented in any manner around the incident beam as axis, but for diffraction to occur they must be so set that the angle of incidence is correct. This is based on the set of conditions known as Bragg's Law, which is written

$$n\lambda = 2d \text{ Sin } \theta,$$

where n is any whole number, λ is the wave length of the particular X-radiation used, θ is the angle of incidence, and d is the interplanar spacing in Angstrom Units (1 Angstrom equals 1×10^{-8} cm.). Thus, in the powder method of X-ray analysis, λ is constant for any one type of X-radiation, the arc sub-

tended by θ is measured along the film, and d is determined by solving Bragg's Law. Tables have been calculated by various agencies and manufacturers that require only occasional interpolation rather than the actual solution of Bragg's Law.

With the equipment used in this study, when the conditions of Bragg's Law are fufilled, diffracted beams are recorded on a cylindrical film whose axis is perpendicular to the incoming rays. In this manner, beams are recorded which are bent through all angles approaching 180°. The rays diffracted through small angles will appear as arcs around the exit hole in the film; the beam diffracted 90° from the incident beam direction will appear as a straight line in the center of the film; and the rays whose diffraction angles approach 180° will appear as arcs near the incident hole in the film.

Many circular cameras are constructed so that there is a direct relationship between the length of the film and the diffraction angle. For example, with the 114.59 mm (effective) diameter camera, 2 mm measured on the film is equal to 1° Bragg. Obviously, this greatly simplifies the calculation of d values.

The powder method may be used in the determination of grain (particle) size, presence or absence of any preferred orientation, and the presence of "grain distortion" as well as the actual determination of an unknown mineral or group of minerals through measurements of their interplanar spacings.

If the material X-rayed is characterized by a definite crystal structure and is reduced to a powder in which the particles average 1 micron (10^{-3} cm) in size, the resulting pattern will be one of sharp lines. The lines will lie at angles characteristic of the mineral and each line will also exhibit characteristic intensity. If it is assumed that the aggregate of crystalline particles has an average size of 1 micron, there are five factors that may influence the width of a given diffraction line:

1. Size and shape of the specimen.
2. Dimensions and disposition of the collimating slits.
3. Angle of diffraction (position of the line on the film).
4. Specimen temperature.
5. Presence or absence of a focusing device (1).

However, the lines may broaden independently of any of the above five factors if the average particle size decreases sufficiently. The broadened lines are termed *bands* or *halos*. Barrett (2) states that the typical halos indicative of the "amorphous" state are present when the crystallites are about 10 Å in size. According to Bragg (3), when the particles become of the order 10^{-6} cm, the diffracted beams will be diffuse regardless of any adjustments to the X-ray system. Lonsdale (4) states that "as the particle size decreases to molecular or atomic dimensions the rings on a powder photograph will broaden until they correspond to those typical of an amorphous solid or liquid."

Even in the finely-divided or amorphous state, the existence of interatomic binding and the impossibility of atomic interpenetration imply the probability of certain atomic arrangements rather than the complete random orientation

of the atoms (3). Experimentation has shown that "amorphous" compounds give patterns that are characteristic within limits. The limiting factor is the diffuse aspect of the halo which prevents accurate measurement, even with the aid of a densitometer.

MINERAL MATTER IN COAL.

The presence of impurities in coal has been the object of study by chemists, geologists, and fuel technologists for many years. These studies are important for fundamental scientific reasons as well as for their obvious application to industrial uses. Information contained herein is concerned primarily with the actual identification of the mineral matter present in the coals, and not with the manner in which they were incorporated nor their ultimate origin.

Mineral matter in coal may be divided into (a) inherent mineral matter or (b) extraneous mineral matter. The meaning of the term "inherent mineral matter" has become rather confused through improper usage, but it is generally defined as "that portion of the mineral matter organically combined with the coal" (5). This type of mineral matter is usually detected through means of spectrographic analyses and consists of such elements as iron, calcium, potassium, and magnesium. Extraneous mineral matter is that which is foreign to the coal-forming plant material. The manner of occurrence is not specified, indeed, two extraneous mineral impurities in the same coal sample may have different origins. The methods of identification of the minerals are varied to suit the individual mineral and include thin section, chemical, oil immersion, X-ray, and determinative mineralogical tests. The presence of extremely fine extraneous mineral matter can be detected by spectrographic means, but the constituents are given in terms of oxides rather than in terms of minerals.

X-ray studies of the coals from Logan County, West Virginia revealed the presence of five crystalline, extraneous mineral impurities, which are of very small grain size. These minerals are (a) kaolinite, (b) pyrite, (c) quartz, (d) calcite, and (e) dolomite. *Kaolinite* ($H_4Al_2Si_2O_9$—monoclinic) is the most widely distributed impurity in the Logan County coals. This mineral may occur with coal in cleat joints and cracks, in fusain and rosin rodlets, in attritus or ground mass of the coal, and replacing plant tissues. The occurrence of kaolinite in the coals sampled appears to be confined largely to the ground mass of the coal. The completeness of the diffraction pattern of many of the solid samples containing kaolinite attests to the finely divided nature of the particles and to their general random distribution. Only one sample exhibited any tendency toward a preferred orientation. Table I is a comparison of the "d" (interplanar spacing) values calculated from Sample No. B-12 and those cited by Nagelschmidt (6) with indices assigned by Gruner (7). Figure 1A is typical of the kaolinite diffraction patterns received from many of the solid coal specimens.

Quartz (SiO_2—hexagonal) may be entirely absent in a coal seam or it may constitute the chief impurity. The quartz grains may range from less than one micron to more than 500 microns in diameter, but the average is from 20

to 75 microns in diameter. The diffraction lines from quartz in coal are often spotty and the patterns are incomplete, usually not more than six lines are present. *Pyrite* (FeS_2—isometric) is the best known impurity in coal. When of megascopic size it is recognized by its hardness and characteristic color. Pyrite patterns were relatively rare in the solid coal samples, but common in the composite powder samples, thus indicating that it occurs mainly in lenses

TABLE I.

COMPARISON OF CALCULATED INTERPLANAR SPACINGS OF LOGAN COUNTY COAL SAMPLE NO. B-12 WITH THOSE OF NAGELSCHMIDT (6).

Logan County Sample No. B-12		Nagelschmidt Aue		Indices (Gruner)
d(Å)	I	d(Å)	I	
7.25	vs	7.15	vs	002
4.44	vs	4.46	vs	110,11$\bar{4}$
4.18	s	4.17	s	021
3.86	vs	3.86	m	022
3.61	s	3.61	vs	00$\bar{4}$
3.36	vw	3.36	w	11$\bar{3}$
—	—	3.09	vw	113
2.75	vw	2.782	vw	13$\bar{2}$
2.59	m	2.570	s	20$\bar{2}$,13$\bar{2}$
2.51	m	2.502	s	006
2.37	s	2.355	vs	20$\bar{4}$
2.29	m	2.297	s	22$\bar{2}$
2.22	vw	2.205	vw	134
2.00	w	1.996	m	20$\bar{6}$,204
—	—	1.953	w	004
1.82	w	1.848	w	13$\bar{6}$
—	—	1.794	w	008
1.66	vw	1.670	vw	136,240
—	—	1.632	m	20$\bar{8}$,31$\bar{4}$
—	—	1.591	vw	24$\bar{4}$,242
1.54	w	1.547	w	13$\bar{8}$,312
1.50	m	1.493	s	060,33$\bar{2}$
—	—	1.455	vw	062,330
—	—	1.396	vw	048
1.38	vw	1.375	vw	064
—	—	1.344	m	208,33$\bar{6}$
1.31	vw	1.311	m	13$\bar{1}$0
—	—	1.287	m	—
—	—	1.243	m	—

vs—Very Strong; s—Strong; m—Medium; w—Weak; vw—Very Weak.

and bands rather than as disseminated particles. *Calcite* ($CaCO_3$—hexagonal) is a rather common mineral impurity in coal. It occurs both as detrital matter deposited during the peat stage and as secondary deposits along open fractures after the compaction of the coal. As with quartz, the diffraction lines are often spotty and the patterns incomplete. *Dolomite* ($CaMg(CO_3)_2$—hexagonal) is a rare mineral impurity in the body of the coal. It was detected in several of

the powder specimens but is thought to be present as a mechanical impurity introduced during the sampling of the coal seam. The "rock dust" commonly used in the mines to prevent coal dust in the air is often high-grade dolomite, and although care was taken not to include rock dust in the sample, enough of it is apparently present in some samples to be detected. In this respect, it is significant to note that dolomite lines cannot be positively identified in the solid coal specimens.

Considering only those coal patterns with crystalline impurity lines which could be accurately measured, kaolinite occurs in 94 percent of the patterns, quartz in 85 percent, pyrite in 41 percent, calcite in 35 percent, and dolomite in 9 percent. In addition to the lines indicative of the above mentioned minerals, 29 percent of the patterns show two lines which could not be positively identified. These lines represent spacings of 2.0745 Å and 2.0376 Å.

PREVIOUS WORK.

Until the advent of X-ray diffraction methods, any compound was termed *amorphous* if it showed no signs of crystallinity under the optical microscope. X-ray studies have proven many substances formerly classified as amorphous to be crystalline, with the particles being too small to distinguish even with the aided eye. These studies have also shown that amorphous compounds are comparable to liquids in that neither possesses a regular crystalline structure (2).

Coal has, for many decades, been considered an amorphous material. The diffraction patterns of coals are found to be typical of amorphous substances or liquids; that is, they exhibit a small number of diffuse bands or halos at medium to low angles. These halos may be partially obscured by background scattering as in the case of most bituminous coals. The X-ray investigation of coal began as early as 1912 when Garrett and Burton (8) discovered that certain crystalline mineral substances enclosed in coal, e.g., pyrite, gave distinctly visible outlines on X-radiographs.

Many early workers, including Debye and Scherrer, were interested in the X-ray study of "amorphous" substances, especially in their relationship to their crystalline equivalents. In attempting to determine the structure of graphite, Debye and Scherrer (9) found that amorphous carbons gave diffraction patterns of halos, which occurred in the region of the principal lines of the graphite pattern. (The lines to which they refer are thought to be those of spacings 3.37 Å, intensity 100, and 2.03 Å, intensity 60.) Debye and Scherrer concluded that the "amorphous" carbons were, in effect, microcrystalline graphite. In 1922, Asahara (10) stated that, based on X-ray studies, "amorphous" carbon "is the ultimate form of the graphite series and not the third modification of the element carbon."

Lowry and Bozorth (11), in 1928, made note of a phenomenon that should be considered in the study of coal, namely, that while the diffraction patterns of graphite and "amorphous" carbons are in general accord, the spacing of the basal plane increases as the average particle size diminishes, and at the same time, the spacings of planes {100} and {110} decrease. This fact was noted

by Riley (12) who gives some detail on the spacing variations. The same phenomenon has been noted and explained by Bacon (13) and Franklin (14).

The significant work of Krishnimurti and Mahadevan in 1929–30 will be discussed in some detail in a later section. Krishnimurti (15) made specific mention of the presence of low-angle scattering in connection with his work on carbons. From this low-angle scattering he deduced that the "amorphous" carbon was in a state intermediate between true amorphous and true crystalline compounds which he termed the "para-crystalline" state.

Working with two components of bituminous coals, vitrain and durain, Mahadevan (16) found that the vitrain gave patterns with two diffuse bands with spacings of 3.38 Å and 2.12 Å and considerable background scattering. He attributed the diffuse aspect of the bands to the colloidal nature of the diffracting particles and suggested that the halos were due to complex carbon molecules in the vitrain. Riley (12) ascribes a similar phenomenon, asymmetry of the {002} line, to the presence of bitumen. Mahadevan also found that the diffraction pattern varied in intensity with the amount of water present in the vitrain. Lines indicative of crystalline material were detected in the diffraction pattern of durain. The lines occurred at spacings of 5.49, 4.31, 3.38, 2.49, 2.13, 2.02, 1.80, and 1.69 Å. The lines of spacings 4.31, 3.38, and 2.49 were later found to be associated with the ash, which was mainly silica and alumina.

Brusset, Devaux, and Guinier (17) found that certain recent lignites produce diffraction patterns similar to those of coals of higher rank and to those of "amorphous" carbons. From the diffraction patterns, they concluded that coals are composed of particles in which the carbon atom arrangement is that of a graphite crystal and that the diffuse nature of the bands is possibly due to the extremely small size of the elemental crystallites. From the width of the band, Brusset et al. calculated the dimensions of the crystallites. They also point out that a diffusion spot occurs "in the immediate neighborhood of the direct path of the rays." The existence of such a central diffusion spot is thought to be characteristic of the "scattered state of the material." The central diffusion spot, which is construed to be low-angle scattering, was used to determine the size of the elemental particles, and it is immaterial whether the particle is in the crystalline or amorphous state. The workers assigned values ranging from 43 Å to 61 Å to the particles in the lignites studied.

Some of the more comprehensive studies on the X-ray analysis of coals were made by D. P. Riley (18) of Cavendish Laboratory, Cambridge. In studying various types of coals from the British Isles, Riley attempted to classify the coals as (a) gas-type or (b) liquid-type solids on the basis of diffraction patterns. The basis of this classification is Riley's interpretation of the fact that the diffraction pattern of a liquid is a diffuse band, inside of which the scattering decreases continuously as the diffraction angle decreases. Theoretically, true liquids also give a sharp zero angle peak, which has not been observed. On the other hand, gases give weak intensity, diffuse scattering rising to a maximum at 0°. Thus, on the basis of similarity to the liquid or gas diffraction patterns, Riley divided the six coals studied into either liquid-type solids or gas-type solids. He states that the scattering from the liquid-

type solids implies a more regular arrangement of the particles in the coal, whereas the scattering from the gas-type solids implies a completely random distribution of the particles. Average particle size values from 30 Å to 35 Å were cited for the British coals.

In another series of experiments, Riley (19) chose two specimens from the same coal, which he designated as the "bright" streak and the "dull" band. These terms were entirely relative to each other and bore no connection to the Stopes-Wheeler classification. The "bright" specimen was mainly transparent to X-rays, and the "dull" specimen was mainly absorbent of X-rays. The "bright" specimen gave the typical coal diffraction pattern with a diffuse ring of mean spacing 3.58 Å. The pattern of the "dull" specimen was one reminiscent of fibers, such as cellulose or stretched rubber. From these patterns, Riley concluded that the "bright" coal was made up almost entirely of "amorphous" matter with a small amount of a semi-crystallized substance. On the other hand, he believed that the "dull" coal was made up largely of semi-crystallized material with some disordered matter. The "dull" coal was found to contain a mineral impurity identified as illite, a complex mineral of the mica group. From data obtained by orienting the specimen in known directions relative to the bedding, Riley discovered that the illite crystallites had a marked preferred orientation; that is, their {001} planes were preferentially parallel to the bedding plane of the coal. The presence of a new X-ray effect was also noted, namely, the presence of a very intense diffuse ring at approximatly 25 Å. In connection with this effect, Riley states that "this ring is probably related to the size of the fundamental coal particles or micelles and to the way in which they are packed together."

Blayden, Gibson, and Riley (20) are responsible for the most complete statistical study of coals and cokes yet accomplished through X-ray methods. In addition to bituminous coals and their chars, these authors also investigated some purely organic substances, the physical constituents (vitrain, fusain, etc.) of bituminous coals, and various anthracites. This study is one of the few conducted to date with the cylindrical camera, and readily indicates the possibilities of further studies of "amorphous" material using the powder method. The specimens were ground to 200 mesh and extruded (0.5 mm. diameter) using a gum arabic bond.

Changes during carbonization of the a and c dimensions of the crystallites of the coal types studied were calculated and plotted. The results obtained are directly applied to the heat of coalification. An upper limit of 200° C is postulated for low-rank bituminous coal, and it appears unlikely that most anthracites were formed under temperatures in excess of 400° C. One specimen, a Scottish Manor Powis anthracite, showed anomalous conditions of crystallite growth indicative of temperatures of formation in the range 800–900° C.

Further work was done on the broad band inside of, and overlapping, the {002} band, which was first reported by Mahadeven (21) in 1930. This band is referred to as the "γ-band." The effect of the γ-band is to produce a highly asymmetric photometric trace of the {002} reflection. It is interesting to note that the asymmetry of the trace of the basal reflection becomes less pronounced

with increasing coal rank, anthracite giving a symmetrical {002} trace. A sample of a Durham coking coal was broken down into its various fractions, and it was found that the overlapping band responsible for the asymmetry was due in large part to the γ-fraction components. From this the authors concluded that the asymmetric nature of the {002} band trace is the result of the presence of a particular kind of organic material in bituminous coals.

Blayden et al. state that there are two basic chemical processes that take place during coalification, (a) the conversion of a portion of the original vegetal matter into carbon-like crystallites, and (b) the conversion of all, or the majority of, the remaining original material into bitumen. The bitumen crystallites are similar to the carbon-like crystallites, but are characterized by a greater c parameter and their larger lamellar molecules are capable of adjustive movements under the influence of thermal vibration, whereas the carbon-like crystallites form a rigid system. The authors state, "It is the intimate association of these two types of structure which is an essential feature of the structure of bituminous coal." The behavior of fusain, which contains more than 91 percent carbon, during carbonization is cited as evidence to uphold this view. Fusain behaves as a rigid turbostratic system when subjected to temperature increases, indicating that it is the bitumen crystallites which form the mobile system.

In summarizing the foregoing it can be seen that the study of coal using X-ray techniques is not a new line of research. It should be noted, however, that most of the X-ray studies mentioned here were done with the flat film Laue camera, the work of Blayden, Gibson, and Riley (20) being the first serious attempt using the powder method and cylindrical camera. It is evident that certain crystalline impurities in coal can be detected and determined by X-ray means if they are present in sufficient amounts. Pyrite, illite, kaolinite, silica, and alumina have been identified in connection with the coal studies cited. It has been postulated that coal is not truly "amorphous," but is made up of elemental crystallites of graphitic nature and work has been done on the size determination of the crystallites. D. P. Riley has proposed that coals can be classified as liquid-type solids or gas-type solids on the basis of comparison of coal diffraction patterns with those of liquids and gases. Blayden et al. were able to postulate temperatures accompanying coalification of various coal ranks based on the behavior of crystallite dimensions during carbonization. These authors also propose a two-phase structural system for bituminous coals, a rigid system of carbon-like crystallites, and a mobile system of bitumen crystallites.

STRUCTURE OF COAL.

Studies of the chemical nature of coal have been in progress for over a century and much literature is available on this subject. The development of X-ray diffraction in relatively recent years has made available new techniques for the study of the structure of coal, and several workers have offered hypotheses of structure based largely on results obtained through X-ray studies. The X-ray study of coal apparently began in 1912 when Garrett and Burton (8) detected crystalline impurities in coal through the differential opacity of

the coal substance and the various impurities. They mention the possibility of using this method to determine whether the impurities could be removed through washing. The authors were unable, however, to comment on the structure of the coal itself.

The first serious attempt to determine the physical nature of coal through X-ray means alone was apparently made by C. Mahadevan (16) in 1929. Mahadevan's first work on coal by X-ray methods was restricted to samples of vitrain and durain which he states are the only distinct coal types, clarain being a combination of vitrain and durain, and fusain being nearly pure free carbon. The use of the term "free carbon" is not defined in Mahadevan's paper, but is herein construed to mean that carbon which exists in the elemental state, crystal form unspecified. The vitrain diffraction pattern was found to be that of two halos (3.38 Å and 2.12 Å) in the position of the two most prominent graphite lines. Mahadevan suggests that the width and diffuseness of the halos is due to the colloidal nature of the diffracting particles and that these particles are the complex carbon molecules present in the vitrain. Randall (1) believes that the presence of a "complex carbon molecule" is unnecessary and cites the obvious similarity between the graphite diffraction pattern and the patterns of the various "amorphous" carbons, such as those obtained from wood, natural gas, and acetylene. In this respect, it is interesting to note that Randall states, "coal, apart from mineral 'ash content,' may be regarded from the physical standpoint as a complex of an amorphous nature." (1, p. 196) He previously defines the term *amorphous* as used in connection with carbon, to be that carbon with crystals, if any, too small to be detected with the microscope. It appears that the term *amorphous* is based purely on optical grounds, or the resolving power of a given microscope. It is suggested that the meaning of amorphous be amended to include only those substances that show a complete lack of crystallinity by all possible investigating methods. Randall also postulates that free carbon is present in the vitrain and that it is of very small particle size and of graphitic nature, but he could not offer an explanation for the general or background scattering. It is possible that both Mahadevan and Randall are partly correct and that both graphitic carbon and a carbon complex occur in vitrain. It is certain that such elements (C, H, O, N) necessary to make up a carbon complex occur in coal substance, and, as Mahadevan points out, coal yields benzenehexacarboxylic acid (mellitic acid) on oxidation which is strong evidence of complex molecules. However, the marked similarity between the spacings of the two most prominent lines of the graphite pattern and the halos of vitrain (or a composite coal) is too great to be ignored. It is reasonable to assume that the halos are due to the particles of graphitic carbon present in the "free" state and that the general scattering is due to the complex carbon molecules that may be present (a) as hydrocarbons in the gaseous state, or (b) as any complex molecule, state unspecified with complete or nearly complete random orientation. While it is true that the diffraction pattern of most gases attain an intensity maximum at 0°, it is probable that only general scattering will be observed unless a certain concentration is present.

With the durain, Mahadevan found that several rings occurred and that partial overlapping was present. He states, "it is shown that the superposition of the 'ash' and graphitic carbon rings on vitrain rings gives the durain pattern, thus supporting the suggestion of Fermor (22) that durain belongs to a colloidal system of the suspensoid type where vitrain acts as a dispersion medium, and the ash and vegetable detritus (with free carbon as end product) as disperse phases." (16, p. 79) This comparison of coal and a liquid (or gel) is important and will be discussed later.

Vitrain and durain were separated into their alpha, beta, and gamma constituents. When a bituminous coal is treated with pyridine, the insoluble residue is termed the alpha compound; the extract from this treatment is in turn treated with benzene which gives an insoluble residue, the beta compound, and an extract, the gamma compound. These constituents are among the thirty-odd chemical compounds which may be extracted through the application of pyridine, benzene, and other solvents. The alpha, beta, and gamma constituents were studied by diffraction methods. Because of (a) the possibility that the above mentioned solvents may combine with or alter the natural constituents of the coal, and (b) the certainty that the solvents give some type of X-ray diffraction pattern, the results obtained from the study of these constituents are of doubtful validity and only one point will be discussed. That point is the fact that the durain residue insoluble in pyridine gives a diffraction pattern similar to that of the durain except that the general scattering is absent. From this phenomenon, Mahadevan deduced that the material responsible for the general scattering had been taken in solution by the pyridine. Riley (12) states that when the derivative of coal is removed by pyridine extraction, most of the asymmetry of the {002} trace disappears, and further states that the asymmetry must be caused by the presence of bitumen. The conclusions as to the cause of this phenomenon could be amplified to include: (a) that the general scattering was due to the carbon complex which was removed by the pyridine leaving the graphitic carbon and thus the halos, or (b) that the diffraction maximum of the pyridine was such that destructive interference took place between it and the general scattering in that particular region, nullifying the effects of both.

In another series of X-ray experiments, also done in 1929, Mahadevan (23) chose specimens of fusain, graphitic anthracite, fibrous and non-fibrous peat. The fusain pattern is one reminiscent of fiber, with relatively sharp carbon and ash rings and little general scattering. The graphitic anthracite pattern also shows little general scattering and the halos are well defined. In connection with these specimens, Mahadevan states, "there is no evidence of the colloidal state in anthracite—either in carbon or in ash. The carbon seems to be here (as also in fusain) in a free state." (23, p. 457) In other words, the halos of the anthracite pattern, although they appear at approximately the same spacings as do the halos in vitrain, are no longer due to the "complex carbon molecule" but to the carbon particles present in the free state. Chemical analyses of bituminous and anthracite coals show that the same basic chemical components appear in each, but in varying amounts. Thus, it seems more logical to assume that the halos in both vitrain and anthracite are due to graph-

itic carbon, while the absence of general scattering in anthracite is due to the small percentage of the carbon complexes present as compared to the vitrain. There seems little need to assume the "greater purity" and the "slight tendency toward orientation" of the particles in the anthracite pattern, or the "greater chemical complexity" of the bituminous coal as suggested by Randall to account for the differences between the anthracite and bituminous diffraction patterns. Randall has previously stated that vitrain contained free carbon of graphitic nature and the diffraction patterns show that the orientation of these particles is no less in bituminous coal than in anthracite; however, there may be a difference in the particle size.

The diffraction pattern of the ordinary variety of peat shows the presence of the "colloidal state." Again, this is construed to mean that fairly heavy background scattering is present on the film. In conclusion, Mahadevan states, "from a parallel relationship of the spacings given by peat to those of the coals, it is suggested that there is a close relationship between peat and coal, the difference between the two being mainly one of structure, rather than of composition." It is thought that this statement is sound, but it is incompatible with statements previously made by Mahadevan, for instance, that free carbon does not exist in vitrain and that the halos are due to complex carbon molecules, but free carbon does exist in anthracite and those same halos are now due to that carbon. It seems certain that there would be a compositional difference, especially if coals are considered in bulk rather than in detail, in the presence of carbon complexes in vitrain and their complete absence in anthracite.

Mahadevan's (24) third series of experiments was performed on vitrain samples alone. The vitrain specimens were from upper Paleozoic and Tertiary coals. All of the samples gave two halos on the diffraction patterns, but with slightly different values. Spacings of 3.37 Å and 2.12 Å were recorded for the Paleozoic coals, and the corresponding spacings of the Tertiary coals were 3.50 Å and 2.21 Å. It is thought that this spacing difference is quite important and reference will be made to it later. Mahadevan noted that the general scattering, in the region between the direct spot and the halo, was approximately proportional to the sum of the volatile matter and the moisture content, rather than to either individually. The Tertiary coal patterns were slightly different, however, in that about the same intensity of general scattering occurred for an appreciably smaller moisture and volatile matter content. He attributes this to the apparent fact that coalification has not reached the mature stage in the newer coals.

Upon dehydration and removal of the volatile matter the general scattering was found to nearly disappear. With dehydration alone, the scattering cleared to some extent, and this is precisely what is to be expected since the main water halo lies in the same area (about 3.35 Å) as does the primary line of graphite (3.37 Å), and although not mentioned, the slight clearing probably took place around the main halo of the coal pattern. Also, freeing the coal of its volatile matter should, as advocated here, tend to clear up the background scattering, since it is believed that the general scattering is due to the carbon complexes present in the form of volatile matter. The removal

of the volatile matter and moisture would relatively increase the carbon content toward that of an ideal anthracite, and therefore, increase the relative intensity of the carbon halos. These changes were accompanied by an increase in the width of the halo for which there does not appear to be on explanation.

It can be seen that this relatively early series of experiments on the structure of coal constitutes a significant contribution in this field. It is probable that some of the conclusions drawn from these experiments are, at least, questionable, but they served to direct the interest of other workers to this line of research.

It seems logical, at this point, to digress slightly from the discussion of the structure of coal and take up the diffraction patterns of liquids. This is not as wide a diversion as may be thought as a comparison of the diffraction patterns of coal and various liquids will demonstrate.

Banerjee (25) believes that in a crystalline solid the constituent "molecules are arranged in perfect regularity except for limited heat oscillations and accidental imperfections," and that this arrangement is preserved because the mutually attractive and repulsive forces among the atoms and molecules are so great that those atoms and molecules execute oscillations about certain mean positions. In gases, the molecules or atoms are so far apart that their forces are negligible and their distribution is considered to approach complete randomness. The liquid state may be thought of as one intermediate between solids and gases. There are a greater number of atoms or molecules per unit volume in a liquid than in a gas, and while the mutual forces in a liquid are not great enough to bind them to a certain position, they are strong enough to prevent random distribution. Banerjee states that liquids may be investigated in either of two ways: (a) "as a degeneration of the crystal due to heat motion," or (b) "as an exaggerated deficiency in randomness of the gaseous state."

K. Lonsdale (4) states, "the atoms in a liquid cannot approach closer than a certain minimum distance to each other, and that one atom cannot have more than a certain maximum number of neighbors," but "there will be in the liquid certain preferred distances between atoms or molecules, and these will give diffraction rings of varied sharpness." This conclusion by Lonsdale is apparently based on the results obtained by earlier workers on the X-ray diffraction of liquids. Debye and Scherrer found that by passing a beam of X-rays through a column of a liquid, the resulting diffraction pattern was one of a broad halo surrounding and at some distance from the primary beam, and that scattering at very small angles was very weak. X-ray diffraction by gases, on the other hand, has been found to increase as low angles are approached and no definite halo can be observed. Later work has led to the conclusion that even in the liquid state there is a definite tendency for the formation of temporary structural units that approach crystallographic regularity. Neither the life nor the configuration of these units is constant, but is a function of the temperature (thermal vibration) and pressure. From this data, liquids are considered as solids possessing fluidity rather than as gases possessing cohesion. Experimental data have also shown that the dif-

fraction maxima of a liquid occur in the regions of the most intense diffraction lines of the crystalline equivalent. The term *regions* is used because the diffraction maxima of liquids are always diffuse halos that increase the difficulty of accurate measurement. A striking example illustrating this point is an X-ray diffraction pattern of melting ice, where the pattern is one of a diffuse halo superimposed on sharp spots. Numerous other examples of this phenomenon may be cited, but the important fact is that these patterns show that the structural break between a solid and its liquid is just as sharp as one would expect from the sharpness of its melting point and the change in physical characteristics.

As previously stated, the diffraction pattern of coal, or of any other fine-grained, high carbon compound, is very similar to that of a liquid. Both show low-angle scattering, at least one halo at medium angles, and general scattering may or may not be present. It should be noted at this point that the halo of the water pattern appears at the melting point of ice, but no such sharp structural break can be demonstrated in the degeneration of graphite to carbon black. The carbon black is still a solid, yet the diffraction pattern is one of a broad halo in the region of the primary graphite line. There can be little doubt that the change from sharp lines to diffuse halos, all in approximately the same angular position, in the carbon series is a function only of the relative particle size. Hence, if this is true, there can be no connection here with the constantly changing structural units apparently present in a liquid. From this, it seems that an anomalous condition exists in which the same X-ray diffraction effects can be obtained from two physical conditions: (a) a solid of extremely fine particle size, and (b) a liquid in which characteristic structural units are present for a time, dependent on pressure and temperature.

Low-angle scattering by liquids, gases, and certain solids has been the basis for many X-ray studies since the effect was first noted by Krishnamurti (15) in his work on carbon black. As noted above, gases give weak intensity scattering that rises to a maximum at 0°, whereas liquids give a diffuse ring inside of which the scattering decreases continuously, as the diffraction angle diminishes. It is possible, from theoretical considerations, that a sharp zero angle peak is present in liquids, but this effect has not been observed.

D. P. Riley (18) proposes, on the basis of X-ray study, that coals can be divided into two classes: (a) *gas-type solids,* and (b) *liquid-type solids.* This classification is based upon the supposed similarity of the low-angle scattering of various coal diffraction patterns to that of liquids and gases. Brusset et al. (17) have shown that low-angle scattering is characteristic of the scattered state of any material and is independent of the arrangement of the atoms within the scattering particles. Randall pointed out that the low-angle scattering observed by early workers was found to be due to a peak in the white radiation, but Riley went to considerable effort to insure that this was not the case in his experiments. The diffraction patterns were made with a Laue type camera using CuKα radiation monochromatized by reflection from the basal planes of a crystal of pentaerythrital. In using this set-up, Riley states that since monochromatic X-radiation is used, all of the blacken-

ing on the film has significance. It is doubtful that this statement is precise in that the factor of air scattering has not been accounted for, and unless an evacuated camera was used some of the scattering must be due to air.

Riley used small, solid coal specimens, all representing British coals; three Welsh coals and three non-Welsh coals. The three Welsh coals were classified as liquid-type solids, while the three non-Welsh specimens were termed gas-type solids. He believes that the former type of scattering implies a more regular arrangement of the particles in the solid than does the latter type. In addition to the random distribution of the particles in the gas-type solids, Riley believes that the structural units are separated (center to center) by greatly varying distances and that the size of the particles may vary widely.

The extent of the central diffusion (low-angle scattering) is, in general, inversely proportional to the size of the diffracting particles, but in this case this simple proportion cannot be used because: (a) the limit of scattering varies with the exposure time, and (b) the limit of the diffuse scattering cannot be accurately measured, except with a densitometer. Riley found, however, that there is an obvious difference in the diffuseness of two low-rank coals, a Northumberland house coal and a Yorkshire coal, and an Irish anthracite; from this he was able to conclude that the structural units of the low-rank coals are considerably larger than those of the high-rank anthracite. There is a complicating factor influencing this conclusion, as Riley states, "the degree of diffusion of the central beam depends not only on the size of the constituent particles of the specimen but also on their mutual arrangement," thus it is possible that the particles are more widely separated in the anthracite. On the other hand, it can be demonstrated through conclusions based on the work of Lowry and Bozorth, that the crystallites in a high-rank coal are larger than those of a low-rank coal. However, this is based on the position of the halo as opposed to the low-angle scattering used by Riley. Riley assumed the scattering particles to be of nearly spherical shape (in the liquid-type coals) and estimated the particle diameter of the Welsh coals through the Ehrenfest-Prins relation. This relation states that the most probable intermolecular spacing (Δ) between nearest neighbors is:

$$\Delta = \frac{\lambda}{2(0.815 \sin \theta)},$$

where λ is the wave length of the X-rays in Å and 2θ is the mean diffraction angle for the ring. The particles of the low rank Welsh coals and the Welsh anthracite, respectively, were assigned values of 31 Å and 34 Å.

It should be noted here that the structural differences proposed by Riley were not found in the coals studied in connection with this report. These coals included, in addition to the Logan County high-volatiles, Pennsylvania anthracite, Pocahontas "smokeless" (semi-bituminous), and a Cretaceous low-rank coal. Each of these gave diffraction patterns typical of the liquid-type coals of Riley; that is, the low-angle scattering diminishes from a peak toward low and high angles. That this effect is due to the coal and not the mechanics of the camera is proven by the presence of a sharp line, indicative of a crystalline material, between the low angle maximum and the zero angle

(Fig. 1B). If the low-angle slope of the scattering was due to the "shadow" of the exit tube, the impurity line would not be recorded on the film. The diffraction pattern of the Pennsylvania anthracite can be changed from that of a "liquid-type" solid to that of a "gas-type" solid merely by removing the exit trap of the powder camera, which allows the scattering from the undiffracted beam to contaminate that from the coal. Laue and powder camera patterns of the same coal specimen gave gas-type and liquid-type patterns respectively. Although the geometry of the two cameras is different, the difference in results is apparently due to the lack of an efficient exit trap in the Laue camera that was equipped with a standard lead trap.

Other factors, such as non-standardization of the specimen-to-film distances and exposure time, and the apparent disregard of the effects of air scattering with regard to the low-angle scattering, tend to cast doubt on the results obtained by Riley. Use of an evacuated camera with a suitable trap and standardization of all operating variables would probably prove or disprove the hypothesis set forth in Riley's paper.

Brusset, Devaux, and Guinier (17) made use of low-angle scattering in determining the particle size of various European lignites. This method does not take into account the internal structure of the particles, thus the particles may be made up of an aggregate of crystallites or of an "amorphous" material. The average particle size of the various lignites ranged from 43 Å to 61 Å. They state in conclusion that "for different types of coal, the ordinary diffraction diagrams are very similar, which proves that the arrangement, at a small distance, of the atoms of carbon is nearly constant. On the other hand, the differences that exist in the central diffusion spots show that the micellar state of the material varies in wide limits."

A. Taylor (26) states, "A few Debye-Scherrer photographs of coal are quite sufficient to discourage a study of this very fascinating subject; the broad, diffuse diffraction halos with the numerous superimposed impurity lines do not seem to offer much encouragement for the investigator." While it is true that the structure of coal will probably never be determined through the Debye-Scherrer method alone, the method has its advantages and allows certain conclusions pertaining to the structure of coal to be drawn. The major disadvantage of the X-ray study of coal is that accurate measurement of the limits of the diffuse halos and of the low-angle scattering and the shape of the scattering and diffraction curves is difficult to obtain, and is subject to a high degree of error without the benefit of a low resolution densitometer. In the study of the West Virginia coals, comparisons were made rather than direct measurements except in the rare cases when the limit of scattering and diffraction seemed to coincide and the cut-off was sharp.

There seems to be little doubt about the conclusions of Brusset et al. on the cause of low-angle scattering. Low-angle scattering similar to that given by liquids was observed on all of the coal patterns. Other fine-grained solids, such as chert, also give low-angle scattering but of a different type. The position of the intensity maximum of the scattering varies slightly in some cases, but it is thought that this is due to variation in the relative size of the samples. Because of the lack of necessary equipment, no attempt has been made here to assign values to the size of the scattering particles as Brusset

and Riley have done. No case was found, under normal conditions, which indicates complete random distribution and wide separation of the scattering particles as in the gas-type solids of Riley.

Blayden, Gibson, and Riley (20) are responsible for a series of experiments on coals, cokes, and chars that appear to be the most comprehensive accomplished to date through X-ray methods. Emphasis is placed on the structure of cokes and chars. Cobalt Kα radiation ($\lambda = 1.785$ Å) with an iron filter was used in conjunction with a 45.4 mm radius cylindrical camera. Powder specimens, bonded with gum arabic, were extruded from a 0.5 mm tube. Under these conditions, most of the patterns were made up of two bands corresponding to the {002} and {100} reflections of graphite. Average dimensions of the crystallites responsible for the {002} band were determined through the relation:

$$\beta = \frac{C\lambda}{L\cos\theta},$$

where λ is the X-ray wave length, θ is the Bragg angle of the diffraction maximum, L is the average crystallite dimension normal to the particular set of diffracting planes in the lattice, and C is a constant, assumed to be unity in this case. The {100} line is a cross lattice line and a value of 1.84 has been calculated for C in the above formula. This value was used to determine the relationship between the crystallite dimensions and the half peak width of the {100} line.

A study of the crystallite growth of cellulose, lignin, and glycine during carbonization was made as a preliminary to similar studies of coal. The carbonization process consisted of heating the specimen in stages up to about 2,000° C in a nitrogen atmosphere. These studies show that there is little change in the c dimension of the proposed flat, aromatic molecules up to the 1,200–1,400° C stage, but that the a dimension increases fairly rapidly beginning with the 400–600° C interval. It is concluded that physical, thermal recrystallization is not likely responsible for crystallite growth and some "chemical mechanism" is called upon. The elimination of such elements as oxygen, nitrogen, or sulfur in the 1,300–1,500° C range may represent the chemical mechanism needed.

Experiments on crystallite growth of different rank coals during carbonization utilized specimens from which the inorganic ash had been extracted. The specimens included peat, brown coals, bituminous coals, anthracite, and banded constituents. Many of the photographs of the low temperature cokes and chars gave asymmetrical photometric traces of the {002} band. In general, the peat, brown coal, and bituminous coal patterns showed a fairly regular a dimension increase from 500° C toward higher temperatures. The c dimension of peat increased from 10 Å to 20 Å in the temperature range 700–1,000° C. This rapid growth is attributed to (a) some catalytic effect, or (b) an inherent characteristic of the peat structure. The brown coal patterns showed the same increase, but much subdued. The bituminous coal crystallites increased in the c dimension to the 500–600° C stage, a decrease from this point to the 900–1,000° C range, and a regular increase from this stage. The crystallite growth changes during the carbonization of vitrain

were similar to those of the bituminous coals. The *a* dimension of the fusain crystallites remained constant up to 600° C above which point the growth increase was normal. The *c* dimension remained relatively constant over the entire temperature range, pointing to a closer relation to the organic chars than to the coals. Fusain is thought to be the result of low temperature coalification. In the anthracites subjected to carbonization, the crystallite *a* dimension showed an almost straight line increase after 700° C. The *c* dimension decreases regularly up to approximately 1,100° C with a sharp increase above this temperature.

Blayden et al. have termed the overlapping band, first reported by Mahadevan (21), the γ-band. In order to determine the origin and significance of this band, a coking coal was broken down into its various fractions and each fraction subjected to X-ray study. It was found that the γ-fraction in total yielded a photometric trace with pronounced asymmetry due to the presence of the overlapping band, but that the γ_1, γ_2, and γ_3 extracts all gave symmetrical traces. The authors conclude, ". . . the fact that a mixture of γ_1, γ_2 and γ_3 in their original proportions gave an X-ray powder photograph identical with that of the γ extract, leave little doubt that the asymmetry of the {002} band shown by the X-ray photographs of coal, is due to presence in the coal of organic matter of a particular kind." Saturated and unsaturated hydrocarbons, resinols, resines, resenes, and resin-like substances are thought to comprise the total γ-fraction. The γ-band is not noticeable in high rank coals, anthracite giving a symmetrical photometric trace. It should be noted here that asymmetry of the {002} reflection was not recognized in any of the high volatile coals of Logan County, West Virginia. The possibility remains that structural changes may have taken place during either the extraction of the inorganic ash or of the various fractions to produce the γ-band effect postulated by Blayden et al.

Regarding the statistical structure of coal the authors state, "results indicate that a bituminous coal consists of a structure of flat, aromatic lamellae, built up almost exclusively of carbon atoms and forming turbostratic crystallites with a layer plane spacing of approximately 3.5 Å, together with lamellae of 'bitumen' that are essentially less flat and less aromatic that the 'carbon' lamellae, but sufficiently flat to form a turbostratic system with a layer plane spacing up to 4.5 Å." To account for these proposed structural features, at least two important chemical processes are postulated to occur during coalification "viz., the conversion of some of the original vegetable matter into carbon-like crystallites and the conversion of some or all of the remainder into bitumen."

Early in the article, the authors state that "It is pressing the crystallite theory too far, however, to regard the structure as consisting of minute graphite crystallites: as will be seen below, these crystallites differ in several important respects from graphite." Important *similarities* between the crystallographic nature of the carbon in coal and graphite are not stressed; for example, the simple and obvious relation between the X-ray patterns of bituminous coal, anthracite coal, and graphite (Fig. 2). The {002} plane spacing of the "carbon-like" crystallites of Blayden et al. lie in the region

of the {002} plane spacing of graphite, but this is apparently regarded only as a coincidence. Few workers of today doubt the validity of the proposed bituminous→semi-bituminous→semi-anthracite→anthracite→super (graphitic)-anthracite relation. It is more reasonable to assume that the graphite in super-anthracite had its origin in some lower rank coal than to assume its cryptogenesis in the extreme metamorphism stage.

Most attention has been centered on the diffuse halo of the coal pattern which lies in the region of the 100 intensity line ({002}) of graphite, or at about a spacing of 3.38 Å. As the greater percentage, usually more than 75 percent, of the body of coal is carbon it is reasonable to assume that the

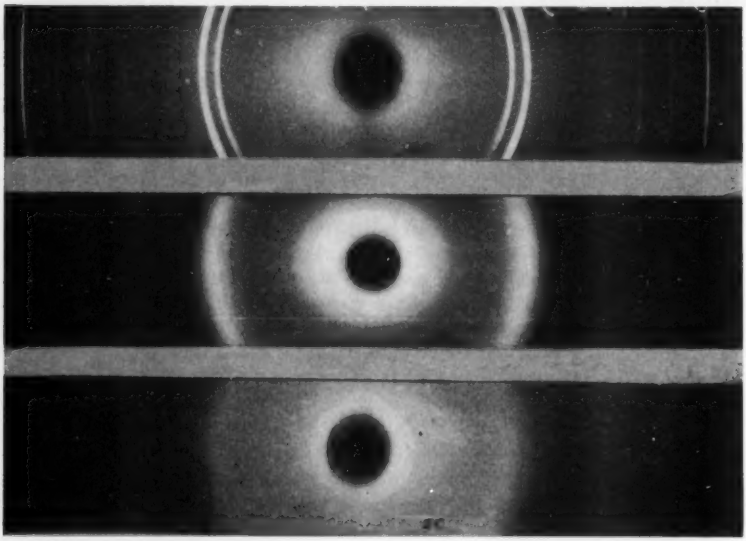

FIG. 2. A. Diffraction pattern of graphite. Fe radiation, no filter. B. Diffraction pattern of Pennsylvania anthracite. Fe radiation, no filter. C. Diffraction pattern of Logan County sample no. 671. Fe radiation, Mn filter. Note absence of impurity lines.

halo is due to carbon in the form of graphite crystallites. This relationship is especially evident in the comparison of the diffraction patterns of graphite and Pennsylvania anthracite (Fig. 2). However, when the typical bituminous diffraction pattern is compared to those of graphite and anthracite a peculiar effect is noted. This is the fact that the halo in the bituminous pattern has a higher spacing (and thus occurs at a lower angle) than the 100 intensity line of graphite or the first halo of anthracite. The difference in the amount of carbon present in anthracite compared to that of bituminous is not great enough to infer that the halo is due to something other than carbon, rather,

it seems reasonable to assume that the effect is due to a structural difference. This structural difference may be explained by the results obtained by Lowry and Bozorth (11) from their work on graphite and "amorphous" carbons. They found that while the diffraction patterns of graphite and "amorphous" carbons are in general agreement, the spacing of the basal plane increases as the average particle size diminishes. This phenomenon would have the effect of decreasing the diffraction angle as the particle size decreases, and the spacing of the basal plane increases. High volatile bituminous coal must be partially made up of graphite crystallites smaller in size and greater in basal plane spacing than those of anthracite, while the crystallites in anthracite must have about the same basal plane spacings as crystals of graphite, although they are too small to produce sharp diffraction lines. Data recorded by Mahadevan indicate that this line of reasoning may be projected to coals of still lower rank, those of Tertiary age. He recorded spacings of 3.37 Å and 2.12 Å for certain Paleozoic coals while the corresponding values of some Tertiary coals were 3.50 Å and 2.21 Å, respectively. The change in spacing of the most prominent coal halo, and thus in change of relative size, leads to the conclusion that the metamorphism which produced the anthracite was also conducive to the growth of the graphite crystallites present in the coal in the pre-anthracite stage.

In discussing the relationship between the rank and heat of wetting (with methanol) of coals as a means of correlation of the rank of coals with their surface areas, Lahiri (27) states, as a possible explanation of the observed phenomena, that "for coals ranging up to bituminous rank . . . the size of the 'micelles' or 'units' of coal in higher rank tends to increase with rank and is about ten times larger in coal of high rank (c 1,000 Å) than in the coals of lowest rank (c 20 Å). This would explain the relative higher moisture content of low-rank coals, as smaller units would have greater interface." Later in the article he states, "Evidently in anthracite, coal has reached a stage where the converging degree of polymerization of the whole of the coal substance produces an assemblage of uniformly larger sized units and shows a recrudescence of surface (or porosity) in spite of higher compaction." The important fact here is that the same conclusion as to the increased size of the structural units in anthracite as compared to bituminous coal can possibly be drawn from two such diverse methods of attack, regardless of whether the units are considered to be polymers or crystallites of graphite.

If, as now it seems certain, variations in phenomena observed in X-ray studies of coal are due to variations in the character of graphitic material, more recent precise work on the structure of graphite itself has direct application to the study of coal.

Papers in this field have dealt mainly with bonding within the graphite structure and with interpretation of the X-ray diagrams given by various carbons. Hofmann and Wilm (28) proposed a graphite model on which most later work has been based. Warren (29) discussed "random layer structures" which consist of layers arranged parallel and equidistant, but random in translation parallel to the layer, and rotation about the layer normal. The diffraction effects observed in carbons indicate structures of this type (Frank-

lin, 30) and are explained as follows: if "a" and "b" are designated as the axes in the layer and "c" is the axis normal to the layer, ". . . there will be reflections of type {001}, two dimensional reflections of type (hk) and no general reflections (hkl)." Warren shows that the two dimensional reflections can be displaced toward larger angles as particle size decreases, the displacement being given by the equation:

$$\Delta(\text{Sin } \theta) = 0.16\lambda/L.$$

"For small particle dimensions L, this displacement of the peak toward larger angles can be quite important. If the two dimensional character of the reflection were not realized and the peaks were treated as normal crystalline powder pattern lines, erroneous conclusions about lattice contractions could easily be drawn." This displacement was observed by Bacon (13) who described *apparent* variations of the "a" dimension of graphite. He also describes a true continuous variation in the "c" dimension with particle size variation.

Franklin (30) discusses the interpretation of diffuse X-ray diagrams of carbon in two extremely important papers. In the latter paper she defines *non-graphitic carbons* as showing only pure two dimensional bands (and {001} reflections) and containing no true graphite structure. Some of these show no development of graphite structure after prolonged heating and are known as *non-graphitizing carbons*. Other *graphitizing carbons* ". . . show a gradual change of the 'random layer structure' . . . towards the ordered structure of crystalline graphite. It has been found possible to prepare a continuous series of such structures intermediate in type between non-graphitic carbons and graphite." To these intermediate carbons she gives the name *graphitic carbons*. X-ray photographs (30, p. 254) show this series. The paper considers the variation in "c" dimension (interlayer spacing) described by others and concludes that ". . . there is in the graphitic carbons a random distribution of oriented and disoriented layers, and . . . that there exist only two possible interlayer spacings, 3.354 and 3.44 Å corresponding, respectively, to orientation and disorientation."

"In the graphitic carbons the graphite-like layers of diameter varying from 80 to more than 600 Å, are grouped in parallel packets of from 30 to more than 150 layers. Within these packets a fraction of the layers are oriented with respect to the neighboring layers as in crystalline graphite, while the remainder are in random disorientation, owing to displacement or rotation in the plane of the layer. The oriented and disoriented layers are sharply differentiated one from the other, and are in approximately random distribution within the parallel packet."

"The interlayer spacing is constant at 3.44 Å in the non-graphitic carbons, and in graphite it is constant at 3.354 Å, whereas in the graphitic carbons the apparent interlayer spacing decreases with increasing graphitization. This apparent interlayer spacing in the graphitic carbons is in reality a mean value. In all graphitic carbons, whatever the degree of graphitization, the small groups of oriented and disoriented layers within the parallel-layer packet retain certain of the structural characteristics of crystalline graphite

and of the non-graphitic carbons, respectively. Among the oriented layers the interlayer spacing is constant and always equal to that in graphite, 3.54 Å. Among the disoriented layers the interlayer spacing is, in the main, equal to that in the nongraphitic carbons, 3.44 Å. But the presence of the more closely packed oriented groups causes some perturbation of the disoriented spacing, 3.44 Å, with the result that among the first disoriented layers on either side of each oriented group there is a spacing of some intermediate value."

The possibility that the bulk of coal material can be considered as *graphitizing carbon* that is approaching *graphitic carbon* with increase in rank, and that the micelles are increasing in size with a decrease in the "c" lattice dimension and with increased orientation of the layers, as described above, is strongly indicated by the results of X-ray study.

X-ray diffraction studies of the physical components of coal are currently being made by Siever (31; Bevan, 32) of the Illinois Geological Survey. Vitrains, fusains, waxes, and other components have been studied utilizing a Laue type camera. Results indicate that there is a greater percentage of crystalline material in the resinic components than in the vitrains and fusains. No conclusion concerning the structure of coal has been made.

CONCLUSION.

From the foregoing discussion, it can readily be seen that the X-ray techniques have become important tools in the study of coal, both from the standpoint of structure determination and detection of crystalline impurities. Coal samples utilized may be either composite (powder) or selective (solid). Powder samples may be coated on Lindemann glass fibers or extruded. The powder method is satisfactory for studies of the structure of coal, but may give misleading data on the presence or absence of crystalline impurities in that they will not be detected unless present in sufficient amounts. In any detailed study of the occurrence of crystalline impurities in coal, the mode of occurrence and the position of the impurity in a coal seam are often as important as the nature of the impurity itself. Clearly, a composite section will not give this information. Thus, it is advocated that for most data, samples should be in solid form taken at desired intervals across the seam. Crystalline impurities in economic amounts are more likely to be detected in solid samples and their occurrences can be accurately plotted.

There are several advantages in using the industrial type powder diffraction unit, as utilized in the study of West Virginia coals. The specimen-to-film distance is fixed, exposure time can be carefully and automatically controlled, and the size of the specimen can be controlled within limits by visual inspection through the slit system. The geometry of the camera permits quick and easy measurement of the diffraction angles along the film. The specimen may be run rotating or non-rotating or may be set at any desired angle about the long axis of the specimen. The same diffraction unit may be equipped with transmission or back-reflection Laue cameras. Although other types of diffraction units offer some of these features, this type is highly versatile and appears to be well suited for studies of coal.

It must be admitted that the industrial uses of the Debye-Scherrer method of X-ray study of coal are limited. Crystalline impurities, if present in certain minimum amounts, can be quickly identified as to mineral constituents and relative quantitative estimates can be made, but those impurities in an extremely finely divided state or those crystalline materials occurring in amounts below the detectable minimum cannot be identified. The X-ray method cannot be compared with the spectrographic method in completeness of the identification of the elements occurring in a given coal, neither can it compete in time required per analysis since eight to ten hours is required for each run in the 114.59 mm camera, although up to four samples can be X-rayed simultaneously, while a complete spectrographic analysis can be made in one man-hour. Where analyses in terms of minerals are desired the X-ray method is more useful since spectrographic analyses are given in terms of oxides.

Scientifically, the X-ray method is important because the extraneous mineral matter in coal can be easily identified, even in polycrystalline form, and certain deductions on the basic structure of coal can be drawn from diffraction patterns. In this latter respect, the X-ray method appears to be far superior to the chemical or spectrographic methods.

There seems little doubt but that coal is, structurally, essentially a two phase system: more or less complex hydrocarbon crystallites that apparently dissociate readily, and graphitic crystallites that are highly stable. Some authors prefer to designate the stable component as "carbon-like crystallites," but non-graphitic. Further work, along the lines of that carried on by Franklin (14, 30), on the isolated stable phase should indicate the true structural nature of the carbon in coal.

Further work should be done to clarify the proposed classification of coal into liquid- or gas-type solids (18). This could only be accomplished by a study of coals from many locations and of various ages under standardized operating conditions.

In conclusion, it is obvious that no one X-ray method is capable of a thorough and precise study of coal, either of the included mineral matter or of the structure of coal. Through a carefully coordinated physical-chemical and X-ray study, it is thought that the structure of coal can be determined to a satisfactory degree.

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DEPARTMENT OF GEOLOGY, CORNELL UNIV., ITHACA, N. Y.,
GEOLOGICAL RESEARCH, INTERNATIONAL NICKEL CO., SUDBURY, ONT.,
Feb. 14, 1952.

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ALLARD LAKE ILMENITE DEPOSITS.

PAUL HAMMOND.

ABSTRACT.

The Allard Lake ilmenite deposits lie in the northeastern part of one of the large Precambrian anorthosite masses which are exposed at intervals along the north shore of the St. Lawrence River, in Quebec. The ore bodies consist of a series of narrow dikes, irregular lenses, or sill-like bodies that appear to be genetically related to the anorthosite rocks in which they occur. The ore is a black, coarse-grained aggregate of ilmenite, which holds numerous oriented microscopic lamellae of hematite. Grade of the material classed as ore averages 32 percent TiO_2, and 36 percent Fe.

The Lac Tio deposit, discovered by Kennco Explorations, Limited in 1946, is the most important ilmenite occurrence in the Allard Lake district and represents the largest body of titanium ore of its type now known in the world. Exploration of this deposit by diamond drilling and surface work has indicated at least 125,000,000 tons of ore in a tabular body 3,600 feet long and 3,400 feet wide, occupying an areal extent of 134 acres. Excellent possibilities exist for materially increasing this tonnage by lateral exploration of the ore body itself, and by the development of several satellite deposits.

An airborne magnetometer survey over approximately 1,000 square miles of the anorthosite mass revealed no previously undiscovered deposits, but served as an excellent means of screening large areas of relatively inaccessible country. Strong negative anomalies were obtained from deposits of massive ilmenite, while in most cases positive anomalies were registered over areas of disseminated ilmenite.

Exploitation of the ore is proceeding rapidly, and recent production of iron and titanium dioxide-rich slag has been obtained at Sorel, Quebec.

INTRODUCTION.

DURING the past five years, developments at the Allard Lake ilmenite deposits have progressed from the early exploration stage to the point where production has been obtained and a new mining camp established.

The deposits are situated 25 miles north of Havre St. Pierre, a fishing village on the north shore of the St. Lawrence River, in Saguenay County of the Province of Quebec. Havre St. Pierre lies 400 miles northeast of Quebec City. Transportation between these points is maintained by aircraft, or by coastal steamers that ply the Gulf of St. Lawrence between March and November.

The presence of ilmenite in this district was first reported by the Quebec Department of Mines following a reconnaissance geologic survey in the year 1941. The ensuing report on this work by Retty (6)[1] describes a number of small ilmenite occurrences along the shores of four lakes in the area. Several

[1] Numbers in parentheses refer to Bibliography at end of paper.

groups of claims were staked, presumably on the basis of the Quebec Government report. Two of these claim groups were optioned by Kennco Explorations, Limited, Canadian subsidiary of the Kennecott Copper Corporation, while a third group was acquired by the New Jersey Zinc Company.

Geologic mapping and surface work were carried out on these showings in 1944. None of these deposits, in themselves, appeared sufficiently large to warrant the major construction expenditures necessary for commercial exploitation of the ore.

In 1946, a major exploration program was conducted in the area by Kennco. This work was designed to investigate an area of 250 square miles in the vicinity of Allard Lake and eastward to the anorthosite-granite contact. Eight separate ilmenite deposits were discovered and staked, including the Lac

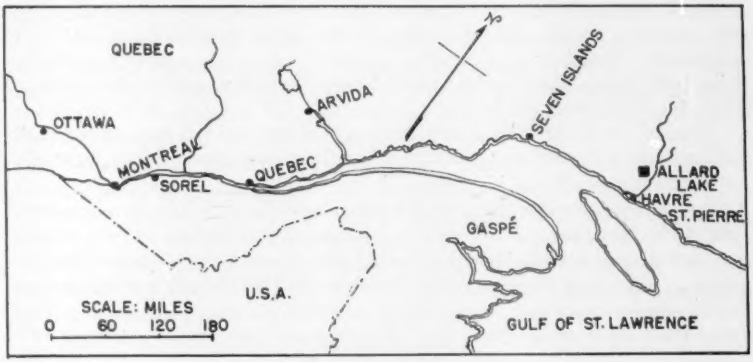

FIG. 1. Location map.

Tio deposit south of Lac Petit Pas. Diamond drilling on this deposit during 1946 and 1947 indicated large tonnages of ore, and plans were then laid to bring the deposit into production.

Construction of a railway from Havre St. Pierre to the Lac Tio deposit began in 1948 and ore is now being mined during the eight-month shipping season. The ore is shipped in from Havre St. Pierre to Sorel, Quebec, for treatment. Operations are being carried out by The Quebec Iron and Titanium Corporation, which is owned by the Kennecott Copper Corporation and the New Jersey Zinc Company.

TOPOGRAPHY.

Along the coast, and northward to the west-flowing portion of the Romaine River, is a flat coastal plain known as the lowlands. The lowlands consist of open muskeg dotted with many shallow lakes and ponds, and underlain by flat-lying Paleozoic limestones. Between the Romaine and Puyjalon Rivers, the ground is flat and sandy and represents part of an old marine terrace.

Beyond to the north, the terrain rises rapidly to form the uplands. Viewed in a general way, the surface has the appearance of an ancient peneplain so that the horizon presents a general uniformity of summits in all directions. In detail, however, the surface is a much dissected plateau with many precipitous cliff-faces and well entrenched valleys. At Allard Lake, the highest summits are 1,300 feet above sea level, with a slope to the south. Maximum relief is about 800 feet but the average relief is between 200 and 300 feet.

Glacial erosion appears to have been an important factor in producing the present topography. The larger lakes occupy north-south troughs, approximately parallel to the direction of ice movement. Many small lakes lie perched in irregular depressions at higher elevations, and the secondary drainage systems have been much disorganized.

The area is drained by the Romaine River system which heads near the Quebec-Labrador boundary. The Romaine flows in a well-entrenched valley, with numerous rapids and falls, which render canoe travel arduous and often dangerous. The river appears to be maintaining its grade against a gradually rising land surface, the Ungava plateau having been depressed by the weight of ice during Pleistocene glaciation.

Throughout the uplands, a thin cover of boulders and soil rests on bed rock, and supports a stunted growth of spruce, balsam, and pine. Many large glacial erratics, most of granitic nature, lie strewn about the surface.

Railway construction through the uplands to the Lac Tio area presented some difficulties owing to the dissected nature of the country and the lack of any well defined valleys in which to maintain a satisfactory grade. In consequence, much rock work had to be done and one 1,500 foot tunnel was driven.

GENERAL GEOLOGY.

The general geology of the district has been well described by Retty (6), and the Morin anorthosite series by Bourret (2).

Allard Lake lies along the southeast margin of the Precambrian shield, close to the contact between Precambrian intrusive and metamorphic rocks and Paleozoic sediments which lie unconformably on the Precambrian along the coast at Havre St. Pierre.

The oldest rocks in the district are of Grenville type, consisting of quartzite, paragneiss, injection gneiss, migmatite, and garnetiferous gneiss. These rocks are best represented in the eastern part of the area, along the Romaine River and in the vicinity of Forget Lake.

The most important lithological unit represented in the area is anorthosite and its allied rock types. The Allard Lake anorthosite is one of several masses of this rock which occur at intervals in the southeastern part of the Precambrian shield, in a line trending northeast from the Ontario-Quebec boundary to the Labrador coast. All of these anorthosite areas lie south of the apparent border zone between Grenville type gneisses and Temiskaming type volcanics. The anorthosites are included in the Morin series (Archean), the name originally applied to a type locality north of Montreal.

As presently outlined, the Allard Lake anorthosite mass is roughly oval in shape with its long axis, about 90 miles in length, paralleling the Gulf of St. Lawrence. The width varies from 20 to 30 miles.

The several facies of the anorthosite vary from an almost pure feldspar rock, through anorthositic gabbro, ilmenite-rich anorthosite and norite.

Anorthosite proper is by far the most abundant facies. It is a dense, light gray, dark gray or pinkish rock weathering to a brownish-yellow or dark gray. It is generally medium-grained although it is coarse-grained or porphyritic. It consists essentially of plagioclose feldspar with a composition range from An_{40} to An_{56}. Dark minerals rarely comprise more than 5 percent of the rock and consist of hypersthene, augite, and ilmenite. The feldspar crystals, in thin section, commonly show granulation along their borders, a fact which suggests that movement has taken place in the rock during or subsequent to its consolidation.

Throughout the area, ilmenite commonly occurs in non-commercial amounts as an accessory mineral in the anorthosite. This rock, referred to in the field as disseminated ilmenite or "mix," occurs along the eastern shore of Allard Lake over a distance of two miles to the east, on Lac Puyjalon north of Lac Manitou, and elsewhere in smaller quantities. The rock is medium to coarse-grained and contains feldspar (An_{50-60}), ilmenite (5–20%), pyroxene, biotite, pyrite, and minor magnetite. It weathers more rapidly than anorthosite proper, and its exposures present a characteristic rust-colored appearance resulting from oxidation of the pyrite.

Anorthositic gabbro occurs principally along the northeast and east borders of the Allard Lake mass. It is a foliated rock, usually coarse-grained, containing feldspar, pyroxene, ilmenite, magnetite, biotite, and a little quartz. The pyroxene is hypersthene so that the rock could be more properly called norite.

To the east and south, the Allard Lake mass is bounded by granite, which is generally coarse-grained or porphyritic. Tongues and masses of granite cut the anorthosite gabbro at certain places along the contact, and pegmatite dikes cut both the granite and the anorthosite. At one point a narrow pegmatite dike cuts a deposit of massive ilmenite.

On traversing from the eastern margin of the anorthosite toward the granite contact the following charges are commonly observed: increasing amounts of pyroxene, biotite, ilmenite, and magnetite, development of foliation which is further accentuated by increase in pyroxene, increasing alteration in the anorthosite, and the appearance of pegmatite dikes and tongues of granite. The contact itself is usually marked by a hybrid zone up to 1,000 feet in width.

From the above information it would appear that the granite is younger than the anorthosite. However, a study of other anorthosite masses in the north shore area indicates that almost all are bordered partially or completely by granite or granite gneiss. Insufficient work has been done at Allard Lake or elsewhere on the north shore to draw further conclusions, but an interesting field remains for detailed petrographic studies on such granite-anorthosite relations.

Bourret (2) expresses the opinion that the Morin anorthosites may have

been forced into the older Grenville gneisses as concordant tabular sheets, or sill-like masses of large areal extent. This conclusion appears justified to some extent in the light of evidence such as the pseudo-stratification shown by certain disseminated ilmenite occurrences.

Flat-lying Ordovician limestones and dolomites lie uncomformably on the Precambrian along the lowlands at Havre St. Pierre, and on the Mingan Islands which lie about a mile off shore.

FIG. 2. Vertical air photograph of Lac Tio area. Scale 1"—2,400 ft. North is toward top. East-west survey lines may be seen north of Lac Tio. Note strong faulting and jointing. Light area on right is burned over.

STRUCTURE.

There is much evidence that the area has been subjected to large scale structural disturbances over long periods, as indicated by the highly contorted and metamorphosed nature of the Grenville-type rocks, and the strong fault and joint systems developed within the anorthosites. In the vicinity of Allard Lake, the anorthosite is cut by numerous joints and faults whose attitude is steeply dipping to vertical. They strike north or northeast and represent faulting of a normal type in which one block has moved down with respect to the adjoining one. These features are everywhere apparent in the topography, giving rise to precipitous, cliff faces. In many instances they are apparent in a series of step-like structures along the hill slopes.

Some of the major faults have been traced for several miles, and some continue without appreciable change in strike beyond the anorthosite body and into the surrounding granite. These fractures are open, and obviously younger than any of the Precambrian rocks of the area.

It is usually impossible to determine relative displacements in an intrusive rock of uniform composition such as anorthosite. However, one major fault has been studied in considerable detail in the vicinity of the Lac Tio deposit, and it appears to have been an important factor in the preservation of the main ore body. Detailed exploration of this ore body has shown it to be in the form of a large, tabular, relatively flat-lying mass, and it can be reasonably assumed that the attitude of the ore was the same at the time of deposition.

A north-south fault, with a steep dip east, cuts through the middle of the deposit and has moved the east side of the ore downward, a vertical distance of approximately 300 feet. There has been, apparently, no horizontal movement. The much greater thickness of ore on the east side of the ore body owes its preservation to this faulting, since it was moved to a deeper horizon and consequently preserved to a greater extent from erosion and Pleistocene glaciation.

ORE DEPOSITS.

All ilmenite deposits so far known at Allard Lake lie in the northeast corner of the anorthosite mass, from two to fifteen miles west of its contact with granite. Six of the occurrences may be classed as being of importance, in that preliminary work in each case has indicated a million tons or more of ore. Of these the most important is the Lac Tio deposit, which is now being mined.

Although all of the deposits are of the same origin, they may be divided into three broad groups on the basis of shape and attitude. These include flat-lying, tabular bodies of large areal extent (Lac Tio deposit and satellites), steeply dipping dike-like bodies (Puyjalon deposit), and lenticular masses which are very irregular in shape (Mills deposit).

The Lac Tio deposit lies between Allard and Puyjalon Lakes, 22.5 miles northeast of Havre St. Pierre. Surface exploration, diamond drilling, and geophysical work have established the deposit as being 3,600 feet in length, 3,400 feet in width, with a surface area of 134 acres.

Surface exposures occupy a roughly rectangular area. From north to south, a comparatively level valley extends from near Lac Petit Pas to the

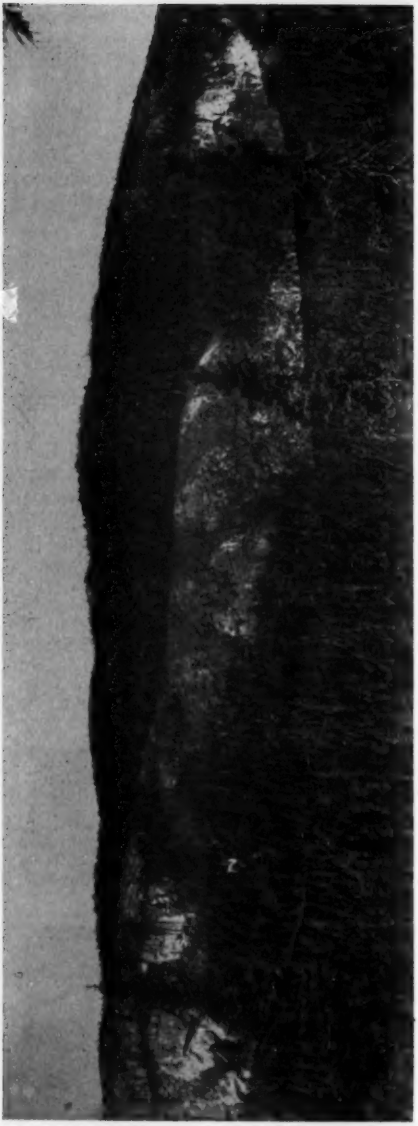

FIG. 3. View of cliff ore body looking west. Darker bluff in center of picture is ilmenite; lighter rock at either end anorthosite.

south end of Lac Tio, a distance of 3,600 feet. There are many exposures of ilmenite in this distance. On the west and east the ground rises rapidly to as much as 440 feet above valley level, and this whole area is known as the main ore body. The cliff ore body lies along the west side of Lac Tio and is separated from the main ore body by a large mass of barren anorthosite.

The main ore body is by far the more important part of the deposit with respect to size, vertical depth, and areal extent. It occupies a rudely rectangular area from which a smaller triangular portion protrudes south along the east side of Lac Tio. Ilmenite is well exposed in numerous outcrops, most of which are oriented in a north-south direction, reflecting the trend of the topography. The ore occurs in anorthosite and anorthosite gabbro, and is identical in character with other deposits in the area.

The ore in the lower lying ground on the central and eastern part of the main ore body comprises the most important and extensive part of the deposit. Diamond drilling in this area disclosed ore to a vertical depth of 300 feet and many of the holes stopped in ore.

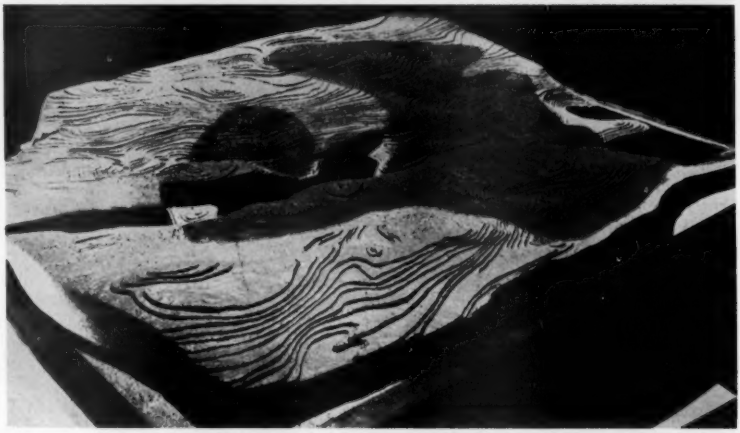

FIG. 4. Model of Lac Tio deposit facing northwest. Dark area underlain by ilmenite as determined from surface outcrops, diamond drilling, and airborne magnetometer results. Scale in center of picture approximately 1200 feet to the inch.

As previously mentioned, a steeply-dipping, north-south fault extending north from the west side of Lac Tio, has moved the east part of the main ore body down a vertical distance of about 300 feet. West of the fault, the ore occurs as a thin, flat-lying body, from 25 to 200 feet thick, with a flat dip west. Near the top of the hill the ilmenite dips flatly under a ridge of anorthosite. Again, 1,200 feet further west, and at the same elevation, ilmenite outcrops are exposed over a length of 2,600 feet and a width varying from 25 to 350 feet. It would appear that this deposit represents a flat-lying western extension of the main ore body.

East of the fault separating the east and west sections of the main ore body, diamond drilling results suggest a basin-like or synclinal attitude, with the deepest ore occurring below the low ground where the bottom of the ore body has not yet been established.

Inclusions and horses of anorthosite as well as zones of disseminated ilmenite are exposed on the surface and have been encountered in drill holes and mining operations. The blocks of anorthosite have no consistency in size, shape, or orientation, and do not show evidence of replacement by ilmenite. They are presumed to represent blocks of country rock engulfed by the ore

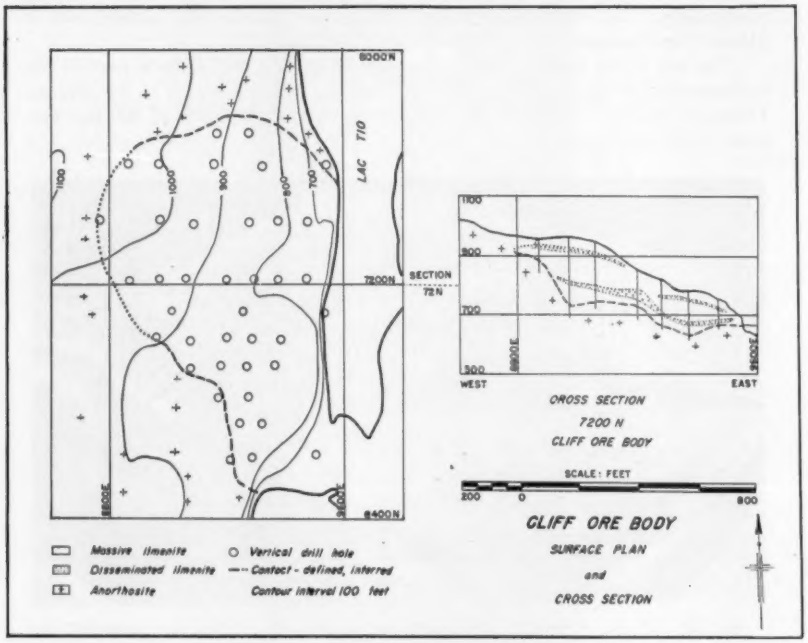

FIG. 5. Surface plan and cross-section, cliff ore body.

during its emplacement. Disseminated ore is commonly arranged in flat-lying or gently dipping bands within the massive ore, and in places exhibits a pseudo-stratification. If a relationship is admitted between the attitude of these bands and that of the massive ore bodies, it further suggests a general flat-lying, tabular habit for the deposit as a whole.

The ilmenite is very coarse-grained along the contacts with anorthosite, and the contacts are very sharp. This suggests that the anorthosite was still hot, but sufficiently consolidated to undergo fracturing when the ilmenite was emplaced.

Estimates of grade and tonnage in the main ore body place the ore reserves as being upwards of 125,000,000 short tons of ilmenite averaging 32 percent TiO_2 and 36 percent Fe. It is the writer's opinion that further lateral exploration will reveal much additional ore.

The cliff ore body is a broad, flat-lying, tabular mass of ilmenite rising 200 feet above the west shore of Lac Tio. The ore body is rudely elliptical in surface plan, with dimensions 1,240 feet in a north-south direction and 740 feet east-west. The average thickness of the ore is 200 feet.

The east side of this ore body is well exposed along the lakeshore. The ore has a relatively even floor, which dips gently to the east. Drilling to the west indicates the ore to extend for a short distance under the anorthosite after which it abruptly dies out.

FIG. 6. Main ore body being prepared for mining. Note strongly glaciated nature of massive ilmenite outcrops. (Photo courtesy of Canadian Metal Mining Association.)

Vertical drill holes on a one hundred foot grid on the cliff ore body show 12,000,000 tons of proven ore of a slightly higher grade than the main ore body. Anorthosite waste and disseminated ilmenite bands are distributed in such a way as to present no serious problems in open cut mining.

A dike-like deposit of ilmenite, known as the Puyjalon deposit, lies two miles south-east of Lac Tio, near the shore of Puyjalon Lake. The deposit strikes northeast and dips southeast at between 60 and 70 degrees. Exposures of ilmenite have been traced for a length of 2,400 feet, and the apparent width varies from 20 to 250 feet. True width of the deposit is somewhat less, since it is exposed along a dip slope.

FIG. 7. Part of main ore body near Lac Tio. Note coarse granular ilmenite grains on surface. (Photo courtesy of Canadian Metal Mining Association.)

On the Mills showing, eight miles southwest of Lac Tio, ilmenite occurs as a series of four massive lenses of irregular shape in one fairly well defined mineralized zone, which extends in a north-south direction for a distance of about 3,000 feet.

NATURE OF THE ORE.

For convenience, the Allard Lake ore is referred to in this paper as ilmenite, whereas it is actually ilmenite-hematite. The ore is dense black, mostly coarse-grained, and is made up of thick tabular crystals. When examined in polished section it is seen that the ilmenite grains include numerous oriented discontinuous blades of hematite. The typical high-grade ore contains approximately 75 percent ilmenite, 20 percent hematite, with the remainder being gangue minerals consisting of pyroxene, feldspar, and minor amounts of pyrite, pyrrhotite, and chalcopyrite.

A laboratory study of these ilmenite-hematite intergrowths by Osborne (5) indicates that within the larger discs of hematite are discs of ilmenite, which in turn contain still smaller blades of hematite. Intergrowths of this type appear to be the result of unmixing of a solid solution since they may be rendered homogenous by heating to a high temperature.

The following table gives the analysis of a number of 25-foot sections of ore from drill holes:

TiO_2	Fe	S	P_2O_5	Cu	V	Mn	Ni	Co
34.8	38.8	0.36	0.004	0.037	0.22	0.08	0.03	0.014
36.0	42.8	0.40	0.010	0.12	0.21	0.08	0.01	0.013
34.4	39.1	0.39	0.012	0.14	0.21	0.10	0.02	0.019

Several hundred analyses of the ore made during the early development work indicated that the iron-titanium ratio is relatively constant. Owing to the marked difference in specific gravity between ore and gangue, the specific gravity of any given sample provides a reliable measure of ore content. A curve, relating specific gravity to ore content, was drawn up on the basis of the chemical analyses, and specific gravity tests taken on all drill cores during development work. The accuracy of this method has been found to be within two percent. This method is now used entirely in controlling grade during mining.

Specific gravity of the material classed as ore ranges from 4.46 to 4.9, which corresponds to a content of 32 to 36 percent TiO_2 and 39 to 43 percent Fe. The present ore being shipped from the Lac Tio deposit contains at least 88 percent iron and titanium oxides, and there will be no difficulty in maintaining this grade without concentration. It must however, be upgraded for the ore itself to be useful for titanium pigment manufacture. Separation of the intimately mixed hematite-ilmenite cannot be accomplished by normal milling practice, regardless of the fineness of grind. The procedure adopted is an electric-furnace treatment of the ore which separates the iron as metal and the titanium as a high titanium-oxide-bearing slag.

GENESIS OF THE ORE.

Almost all known rock deposits of ilmenite occur in association with basic rocks, particularly anorthosite and gabbro in which ilmenite is also usually found as an accessory mineral. There can thus be little doubt of a genetic relationship between ilmenite and rocks of this composition, but no general agreement exists, to date, as to the precise relationships which may exist.

Although the deposits at Allard Lake may vary in shape and attitude, being tabular, dike-like, or lenticular, their relationship to the anorthosite host rocks are always the same. The contacts between ilmenite and anorthosite are sharp. Ilmenite is coarse-grained at the contacts, indicating that the anorthosite was still hot when the ore was emplaced, but had cooled enough to become fractured. Inclusions and irregular blocks of anorthosite within the ore bodies show little if any alteration. Tiny dikelets of coarse granular ilmenite commonly cut the anorthosite at the contacts with the ore bodies. A little pyrite, chalcopyrite, and pyrrhotite are present, all of which occur interstitially. Biotite is found in a few places along the contacts, but there is no aureole of alteration in the wall rocks and no garnet, tremolite, or muscovite have been observed.

On the basis of the above direct field evidence, the writer prefers to class the Allard Lake ores as being late magmatic. A process of late gravitative liquid accumulation with injection of the oxides into fractures within the present anorthosite rock, approximately as defined recently by Bateman (1), presents the most satisfactory explanation of such field observations.

Bateman (1) states that "The low grade disseminated ore bodies in which ilmenite was the last mineral to crystallize, would represent incomplete draining of the enriched residual liquid, or crystallization of a liquid accumulation before purification by elimination of plagioclose and pyroxene could take place. The high grade ore bodies would represent a high degree of purification of the oxides with most of the plagioclose eliminated during extremely slow consolidation."

Work by Gillson (3, 4) at the St. Urbain ilmenite-hematite deposits (somewhat similar to Allard Lake), and at the Lake Sanford titaniferous magnetite deposits, leads him to conclude that a high temperature replacement origin is the probable mode of origin.

Certainly both field and microscopic evidence at Lake Sanford show that a replacement origin there must be entertained. However, it is the writer's opinion that the observed field evidence at Allard Lake does not indicate a hydrothermal origin.

EXPLORATION METHODS.

Preliminary investigation of the original ilmenite discoveries at Allard Lake indicated that all of these were too small to be of commercial importance in such a remote area. However, a detailed exploration program was planned for the field season of 1946, on the theory that where there is "smoke" there must be some "fire." The problem was then one of exploring an area of 250 square miles in the northeastern part of the anorthosite mass where ilmenite had been found along certain of the lakeshores.

Accordingly, a number of geologic prospecting parties were organized who carried out traverses originating from the shores of the larger lakes. Traverses were run at quarter-mile intervals in an east-west direction, normal to the strike of the previously known ilmenite occurrences.

The ground was carefully examined and mapped along the line of traverse and on both sides; and this work was supplemented by dip needle readings at 200-foot intervals or less.

This work resulted in the discovery of eight ilmenite deposits of sufficient importance to justify claim staking. Included in these, was the Lac Tio deposit, which on development proved to be the largest body of titanium ore of its type now known in the world.

Following the usual surface geologic and topographic mapping, a diamond drilling program was begun to explore the Lac Tio deposit at depth. A series of vertical holes at 200-foot intervals were drilled along five east-west sections to an average depth of 300 feet. Core was sampled in 25 foot lengths where ore intersections were sufficiently long, and specific gravity tests were made on all samples before shipment for analysis. Later drilling on the portions of the ore body to be mined was carried out on a 50 foot-grid pattern.

After the success of the first year's exploration program, the problem remained of exploring the remainder of the anorthosite mass for other ilmenite deposits closer to the coast which might be developed with less capital expenditure.

The task of examining the area west of Allard Lake, by the methods previously used, presented many difficulties since the terrain is particularly rough and few lakes exist suitable for landing with float aircraft. Accordingly, an airborne magnetometer survey was planned to search for other ilmenite deposits, or for specific areas in which detailed ground work might be justified.

Details of the organization and operation of the survey have been well described by Bourret (2). Flight traverses were flown in a northwest-southeast direction at a nominal elevation of 500 feet. Some 4,500 linear miles of air traverse were completed in the space of two months. The survey was first carried over the known ore occurrences to determine the results that might be expected, after which the flight lines were carried through to unexplored territory.

No new deposits were discovered as a result of the aeromagnetic survey, but strong anomalies were obtained over all known major ore bodies.

Aeromagnetic Survey Results.—The airborne magnetometer is a sensitive flexgate instrument that measures total magnetic intensity in a field parallel to the earth's total magnetic vector, so that the major portion of the earth's field is nullified leaving relative differences to be measured.

The first series of flights over anorthosite areas established a tentative normal magnetic datum for the area in general to which variations in magnetic intensity might be referred. At the completion of the survey, a common magnetic datum was established by running a magnetic base line traverse to intersect each flight line.

Throughout the interior of the anorthosite mass, the magnetic profiles maintained a relatively uniform pattern with moderate and gently undulating curves remaining in the range between zero and 2,000 gammas. It would thus seem that most of the anorthosite is relatively uniform in composition.

Areas of disseminated ilmenite in anorthosite, with one exception, were characterized by elevations in total field intensity of between 2,000 and 4,000 gammas above that considered normal for the distract. Actual anomaly areas were extensive and the aeromagnetic profiles much less steep than obtained over massive ore bodies.

The foliated gabbroic contact zone on the western side of the anorthosite produced relatively high magnetic intensities, but the profiles were gentle on passing from areas of massive anorthosite to the contact zone. Elsewhere, to the south and east, results were inconclusive and the boundaries between the Grenville and the Morin series could be obtained only approximately.

Massive ilmenite ore bodies of any size were well defined by sharp depressions in field intensity and by small anomaly areas. On passing over the outer boundaries of the Lac Tio deposit, magnetic profiles were characterized by a sharp decrease in field intensity to more than 3,500 gammas below plateau

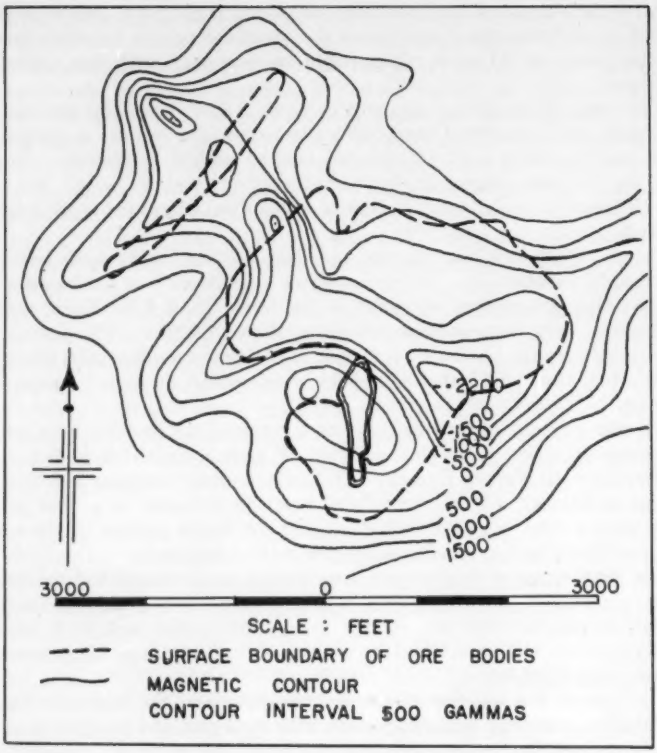

FIG. 8. Aeromagnetic survey Lac Tio area.

level. The actual anomaly area corresponded closely to the known position of the ore bodies as defined by drilling and geologic work, as shown in Figure 8.

The strong negative anomalies are believed to be the result of negative polarization of the massive ore bodies, as similar results were obtained by dip needle work.

The airborne magnetometer provided an efficient and rapid means of exploring for ore bodies in the Allard Lake environment, where the host rocks are relatively uniform in composition and the target is large and slightly magnetic.

ACKNOWLEDGMENTS.

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NORTHWESTERN EXPLORATIONS, LTD.,
402 WEST PENDER STREET,
VANCOUVER, B. C., CANADA,
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STRUCTURAL ENVIRONMENTS OF THE LEAD DEPOSITS IN THE SOUTHEASTERN MISSOURI MINING DISTRICT.[1]

JACK A. JAMES.

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ABSTRACT.

Three principal structural environments favorable for the emplacement of lead ores are associated with distinctive types of lead deposits. The fault zone environment is present along zones of faulting which commonly consist of a large number of individual faults that form an intricate parallel, sub-parallel, and branching pattern. The basic conditions for the knob and ridge environment are basement rock knobs and ridges surrounded by sediments with initial dip and a local fracture system. The structural block environment was created by a combination of folding and faulting movements that produced a reversal in the direction of dip within a triangular section, the Flat River structural block.

INTRODUCTION.

Three principal structural environments favorable for the emplacement of the lead ores have been recognized as the result of regional structural studies. They are formed either by a single or a combination of structural features. The environments are differentiated on the basis of occurrence of mineralization and the geologic setting. A distinctive type of ore deposit is associated with each of the three environments, and the differences between the types of ore deposits are related to differences between the structural environments, thereby focusing attention upon the influence of the environments upon the occurrence of mineralization. The environments and the associated ore de-

[1] Presented before the Society of Economic Geologists joint Meeting with the American Institute of Mining and Metallurgical Engineers, New York Meeting, February 1952.

posits are referred to as the 1) fault zone, 2) knob and ridge, and 3) structural block.

The rock succession in the mining district is a basement of Precambrian extrusive and intrusive igneous rocks overlain unconformably by a sedimentary series ranging in age from Upper Cambrian to Pennsylvanian. The base upon which the Precambrian extrusives rest is unknown. The basement rock was subjected to a prolonged period of erosion, and valleys more than 1,500 feet deep were carved in this surface. The sedimentary series was deposited upon this rugged erosional surface; consequently, the mineralized sediments are separated from the basement rock by a profound unconformity.

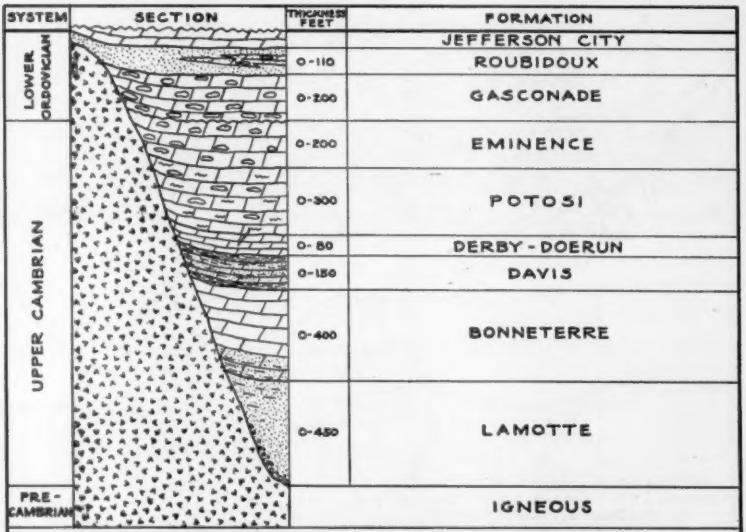


FIGURE 1. PARTIAL COLUMNAR SECTION IN THE SOUTHEASTERN MISSOURI MINING DISTRICT.

The partial columnar section in Figure 1 shows the rough basement rock surface and the overlap relations of the formations. The first Paleozoic sedimentation of record is a basal sandstone, Lamotte formation, followed by an accumulation of carbonate rocks, sandstone, and shale. Lead ores are found principally in the lower half of the Bonneterre formation, although some mineralization is present in all the formations shown in Figure 1.

FAULT ZONE STRUCTURAL ENVIRONMENT.

The fault zone structural environment is present along zones of faulting. Most of the major structural features in the mining district are fault zones,

which commonly consist of a large number of individual faults that form an intricate parallel, sub-parallel, and branching pattern. The rock is ruptured in different degrees of intensity; at some places it is shattered by closely spaced fractures, and at other places it is broken by widely spaced fractures. The intricate pattern of faulting is illustrated in Figure 2 by the Palmer fault zone

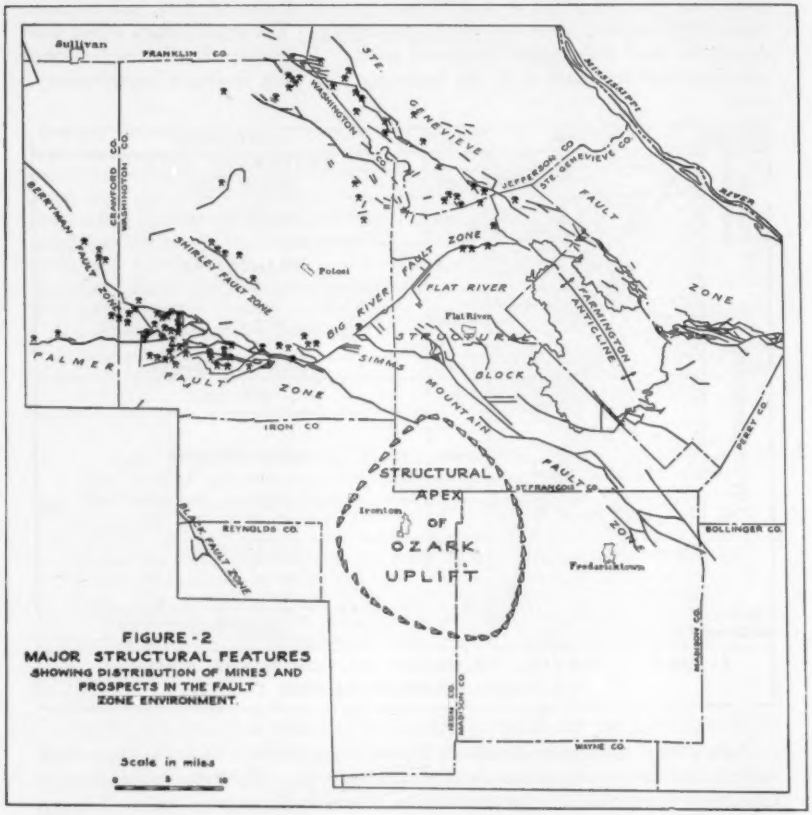


FIGURE - 2
MAJOR STRUCTURAL FEATURES
SHOWING DISTRIBUTION OF MINES AND PROSPECTS IN THE FAULT ZONE ENVIRONMENT.

in southern Washington County. The mapped patterns represent only the largest breaks in a complex system of fractures that extend outward in either direction along the trend of the fault zone.

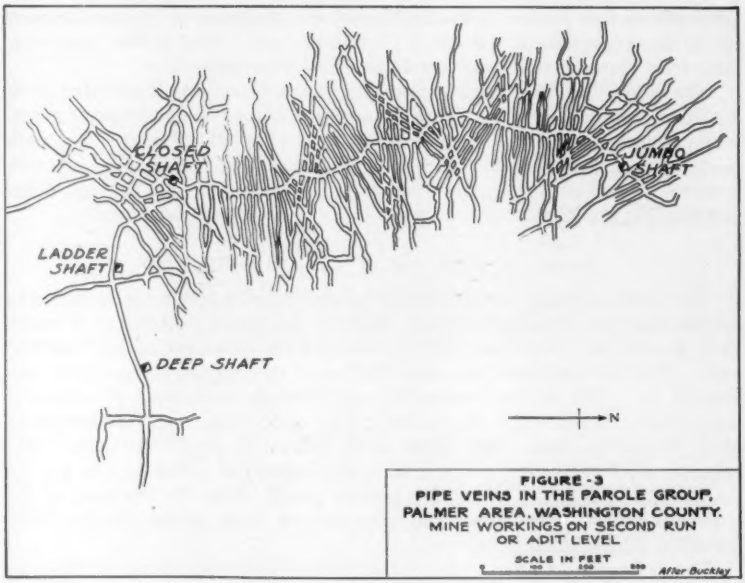
The environment is developed best in the northwest quarter of the mining district, and this area contains most of the fault zone type of lead deposits. The distribution of mines and prospects (Fig. 2) shows that lead ore has been

mined in this type of environment along the Ste. Genevieve, Big River, Palmer, Berryman, Shirley, and Simms Mountain fault zones.

FAULT ZONE TYPE LEAD ORE DEPOSIT.

The fault zone type of lead ore deposit furnished most of the lead production in the early history of the mining district. The mine workings are abandoned now and many are inaccessible.

Galena is the chief ore mineral, although sphalerite, barite, and smithsonite have been recovered from some properties.



The trend of mineralization is marked by a linear system of fractures that have been enlarged at places by solution. The resultant openings are discontinuous along the fractures. They commonly are filled or partly filled with a mixture of clay, loose rock fragments, and gangue and ore minerals. The ore minerals, ranging in size from microscopic crystals to aggregates of crystals weighing several hundred pounds, occur along the walls of the openings, intermixed in the clay and loose rock fragments and, with gangue minerals, form narrow veins in the fractures between openings.

Mine workings in plan view have the long narrow outline common for workings on vein deposits, but the similarity to vein deposits is restricted by the limited vertical extent of mineralization. The fault zone type of lead

deposit has a small vertical dimension, in contrast to the relatively large vertical dimension of vein deposits. However, more than one level of mineralization may be present, as at Valle Mines and in the Palmer area where three levels were developed. The restricted lateral and vertical dimensions prompted Wheeler [2] to use the term "pipe veins" in describing the ore bodies in the Palmer area. These "pipe veins" range in size from 2 to 8 feet wide, and 6 to 48 inches high.

The close relationship of the pattern of ore distribution to the fracture system is illustrated in Figure 3. The alignment of mine workings corresponds to the joint system observable at the surface of the ground.

The stratigraphic position of this type of deposit ranges through nearly 1,500 feet of rock section, from the Bonneterre formation of Upper Cambrian age to the Roubidoux formation of Ordovician age. Most of the production came from deposits at or near the Potosi-Eminence contact.

The mines that were developed on this type of deposit are distributed along the major zones of faulting. Few are within the zone of maximum displacement; instead, they are situated marginal to it (Fig. 2). Hundreds of individual workings on the fault zone type of lead deposit are recorded in numerous localities throughout the mining district. The production from any individual property has not been large, and none of these mines are active today.

KNOB AND RIDGE STRUCTURAL ENVIRONMENT.

The knob and ridge environment is related directly to the configuration of the basement rock erosional surface. Prior to the first sedimentation of record a topography with more than 1,500 feet of relief was developed on the basement rock. The first sediments were deposited upon this rugged surface by an advancing sea. The valleys eventually were filled by increments of successive layers that probably buried the highest points on the basement rock surface in early Ordovician time. The oldest layers formed in the lowest parts of the valleys. Each succeeding younger layer overlapped the preceding one, but the areal extent is limited to the valley pattern except where the thickness of the sediments exceeded the depth of the valley and the strata spread over the dividing ridge, hill, or knob.

The sediments adjacent to the valley walls were carried up those slopes by current and wave action, and the beds or layers turn upward near the valley wall. Compaction of the sediments accentuated the original angle at which the beds turn upward. The combined effect is recognized today as initial dip. Initial dip is reflected most strongly in the oldest beds that extend over the knobs and ridges, but its expression gradually lessens in succeeding younger beds. It causes the layers near the flank of the knob or ridge to be structurally high. This structure is a striking feature of the knob and ridge environment.

Underground observations show both a regional and local fracture system in the sediments adjacent to the knobs and ridges. The regional system corresponds to the pattern noted at the surface throughout the area, and has been

[2] Wheeler, H. A., Report on the Palmer lead property: unpublished report made for H. J. Cantwell, 1928.

omitted from the sketch in Figure 4 in order to show better the local fracture system. The local pattern is related closely to the shape of the knob or ridge at the mining level. The fractures bend with the curvature of the knob or ridge, but they diverge where this curvature is sharp. They do not appear to extend into the underlying basement rock, however, the basement rock is exposed at only a few places in the mines, and this observation may be more apparent than real.

The fracturing in the mines, and the projection of it beyond the mine openings, develops the picture of a band of locally controlled fracturing in the sediments along the flank of a knob or ridge. The band parallels the configuration

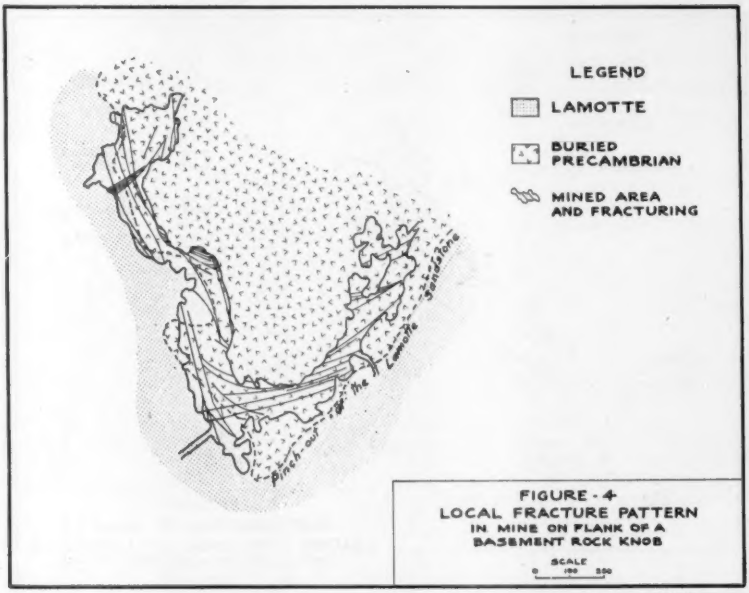


FIGURE - 4
LOCAL FRACTURE PATTERN
IN MINE ON FLANK OF A
BASEMENT ROCK KNOB

of the knob or ridge in plan section and, in more detail, the orientation of the fractures within the band responds to small variations in the shape of the basement rock feature.

A convenient reference line for the position of the band of local fracturing and the position of ore bodies is the pinch-out of the Lamotte sandstone, which also reflects the configuration of the knob or ridge at that level.

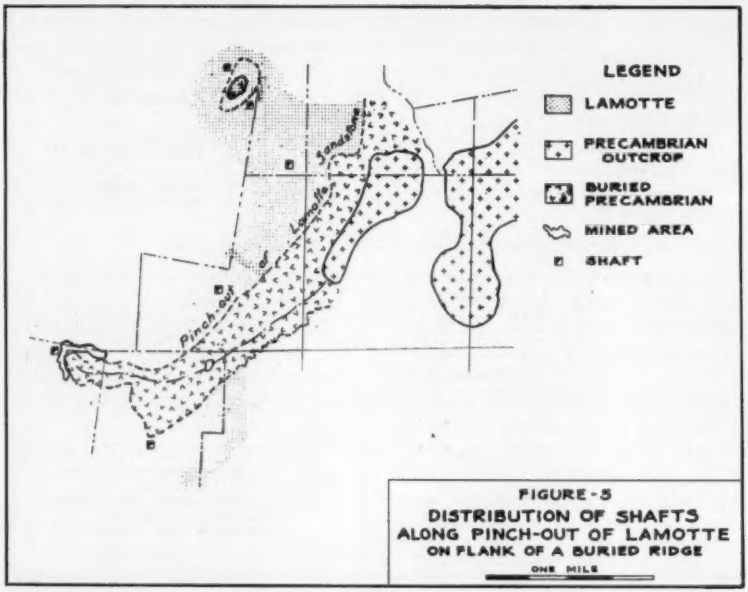
KNOB AND RIDGE TYPE LEAD ORE DEPOSIT.

The knob and ridge type of lead deposit is a minor but important source of lead production. Sixteen mines have been developed in it; eight are active today.

The ore minerals include galena, chalcopyrite, and siegenite. The early mining at depth was for the complex copper-nickel-cobalt ores, but former difficulties in beneficiation caused the mining energies to shift to the extraction of lead ore. Galena is the most important ore mineral now mined.

The mineralization is present as disseminated grains, as horizontal streaks due to replacement along bedding planes, as replacement masses traversing beds, as veins and incrustations along fractures, and as lining in cavities.

The known ore bodies are in the Bonneterre formation, chiefly in the lower 50 feet. A modification in detail exists at a few places where slight mineralization extends into the uppermost beds of the underlying Lamotte formation.

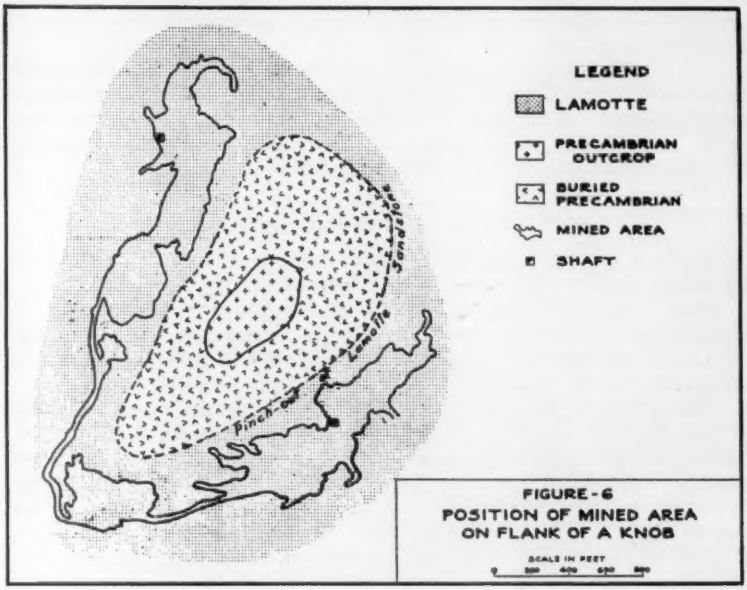


The ore bodies may be 200 feet wide locally, although the average width is about 125 feet. The ore may extend through a height of 50 feet, although it usually is less than 10 feet thick.

The position of the ore bodies in plan view conforms very closely to the shape of the basement rock knob or ridge at the mining level. Figure 5 shows the outline of a buried ridge and the position of several shafts. The outline of mine workings at one shaft suggests the general outline of workings at other shafts. The ore bodies are situated on the flanks of the buried ridge. The discontinuous distribution of ore, and the resultant ellipsoidal form of ore bodies suggest numerous loci of emplacement. The distribution of shafts along the

pinch-out of the Lamotte indicates the conformity of ore body distribution to the configuration of the ridge.

The influence of the knob or ridge upon the position of the ore bodies is evident in smaller scale than shown in Figure 5. Figure 6 shows the position of an ore body on the flank of a basement rock knob. The mine area parallels the contour of the knob at the mining level as indicated by the pinch-out of the Lamotte. The coincident positions of the band of local fracturing and the ore bodies is obvious from a comparison of Figures 4 and 6.



Faulting is recognizable in the mines, but it is of small magnitude and appears to be a secondary influence on ore emplacement. The local fracturing appears to be a more effective structural factor in localizing the ore bodies.

STRUCTURAL BLOCK ENVIRONMENT.

The structural block environment is the environment of the extensive disseminated lead ore bodies of the "Lead Belt." The triangular section bounded by the Farmington anticline on the east, the Big River fault zone on the north and northwest, and the Simms Mountain fault zone on the southwest and south (Fig. 2) is designated as the Flat River structural block. All of the boundary structural features played a part in creating this environment.

The structural block was tilted upward by upfolding expressed by the Farmington anticline. The northern and northwestern portions were upthrown by movement along the Big River fault zone. The southwestern and southern portions were downthrown by movement along the Simms Mountain fault zone. The folding and faulting movements were complementary, and tilted the triangular section upward in the eastern part.

The tilting produced a striking deviation from the general attitude of the sediments around the structural apex of the Ozark uplift. Formations contemporaneous with those in the structural block dip radially away from the apex, but the formations within the structural block dip toward the apex. The combined movements of folding and faulting were sufficient to cause a reversal in the direction of dip.

The southwestward dip is modified locally by the irregular floor upon which the sediments were deposited, and it is broken by numerous faults that attended the deformation. A few knobs that extend into the overlying Bonneterre attest to the irregular floor. The faults reflect the predominant northwest trend of the major structural features in the mining district.

STRUCTURAL BLOCK TYPE LEAD ORE DEPOSIT.

The structural block type lead deposits furnish most of the production from the mining district. They are the famous deposits of the "Lead Belt."

Galena is the principal ore mineral. Mineralization is disseminated, in horizontal streaks due to replacement along bedding planes, in veins along fractures, and as lining in cavities. The major portion of the mineralization is disseminated in the Bonneterre formation which is the favorable host rock.

The ore bodies, in general, are essentially horizontal and occur in a series of beds 20 to 30 feet thick, 20 to 50 feet above the base of the formation. Locally, mineralization is present through a larger vertical interval, and some stopes are more than 200 feet high. More than one level of mineralization may be present, but the ore bodies that are highest stratigraphically generally are less persistent than the lower ones. The lower ore bodies may have a height of 20 to 30 feet, a width of several hundred feet, and a length of more than 1,000 feet.

A northwest alignment of ore bodies is recognizable when the structural block is viewed as a whole, but this trend may not be apparent in an individual mine or a small group of mines. A mine consisting of more than one level may exhibit an alignment on one level and the one above or below it may show either a similar trend, a different trend, or no directional trend.

DISTRIBUTION OF MINERALIZATION AND AREAS FAVORABLE FOR STRUCTURAL ENVIRONMENTS.

Two general questions evolve from the relationship of structural environments and ore deposits. They are concerned with the areal extent of mineralization, especially in the Bonneterre formation, and the distribution of areas favorable for structural environments.

The most widely separated occurrences of mineralization in the Bonneterre formation form the perimeter of an area of about 1,800 square miles (Fig. 7). Rocks older than the Bonneterre are present at the surface over about 500 square miles, leaving nearly 1,300 square miles where the formation is present.

The structural history of folding and faulting creating the Flat River structural block is not recognized elsewhere in the mining district.

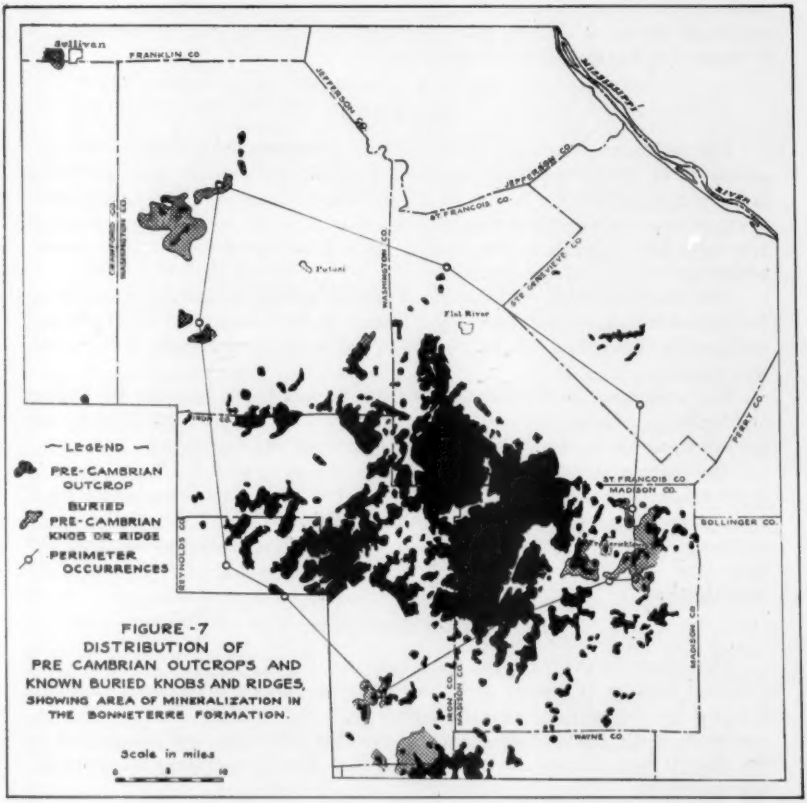


FIGURE - 7
DISTRIBUTION OF PRE CAMBRIAN OUTCROPS AND KNOWN BURIED KNOBS AND RIDGES, SHOWING AREA OF MINERALIZATION IN THE BONNETERRE FORMATION.

The general geologic setting of the knob and ridge environment is indicated at many places. Exposed knobs and ridges of the basement rock surrounded by sediments furnish the basic conditions for this environment. The known areal geology pattern suggests that these basic conditions may be present in a belt of varying width on three sides of the central igneous mass (Fig. 7). The inner margin is marked by an area of non-deposition of the Lamotte sandstone.

The position of the inner boundary is not known precisely everywhere, but it can be estimated rather closely at many places. The outer margin is marked by the outermost exposed basement rock knobs and ridges. Drillhole data indicate this belt contains knobs and ridges not yet laid bare by erosion. Accordingly, the outer margin may be extended, and other favorable areas postulated, in view of the probable buried knobs and ridges not yet located.

The fault zone environment is associated with zones of faulting. Although most major zones of faulting have been mapped, either in detail or by reconnaissance survey, it is likely that other zones of faulting will be discovered as a result of additional field investigations.

SUMMARY.

The fault zone structural environment is characterized by deformation consisting of an intricate pattern of many parallel, sub-parallel, and branching faults accompanied by a multitude of subsidiary fractures. The contribution of fracturing to this environment as a forerunner to the formation of the fault zone type lead deposits is indicated by the conformity of distribution of mineralization to the fracture system.

The knob and ridge environment is related directly to the configuration of the basement rock erosional surface. Initial dip and a local fracture system are components that influenced the position of ore bodies on the flanks of the knobs and ridges.

The structural block environment consists of a block bounded by folding and faulting. The direction of dip of the sediments has been reversed by the deformation that produced also abundant faulting and fracturing.

The pattern of deformation that created the structural block environment is not recognized elsewhere in the district. The basic conditions for the knob and ridge environment are indicated at many places by the known areal geology pattern. It is likely that additional zones of faulting that may develop the fault zone environment will be discovered as a result of additional field investigations.

ACKNOWLEDGMENTS.

This paper is published by permission of E. L. Clark, State Geologist, Missouri Geological Survey and Water Resources, as a preliminary paper to a report on the regional structural geology in the mining district. The cooperation of the staffs of the mining companies operating and prospecting in the district was fundamental to this study. That cooperation is gratefully acknowledged.

MISSOURI GEOLOGICAL SURVEY AND WATER RESOURCES,
ROLLA, MO.,
May 8, 1952.

FIELDS OF FORMATION OF SOME COMMON HYDROTHERMAL–ALTERATION MINERALS.

BRONSON STRINGHAM.

ABSTRACT.

The problems of identification of the fine-grained hydrothermal alteration minerals are fairly well advanced. The fields of formation at which these minerals were formed are not so well known. Some common hydrothermal minerals have been arranged on a chart, the abscissa of which represents the pH of the depositing solutions, while the ordinate represents temperature. The chart is presented with a multiple purpose—i.e., to present in readily usable form the known information regarding the field of formation of minerals; to serve as a stimulus to students to attack the hydrothermal problem from a laboratory viewpoint, and to bring out further information from individuals who may have better data. It is expected that the chart will change from time to time with the accumulation of new information.

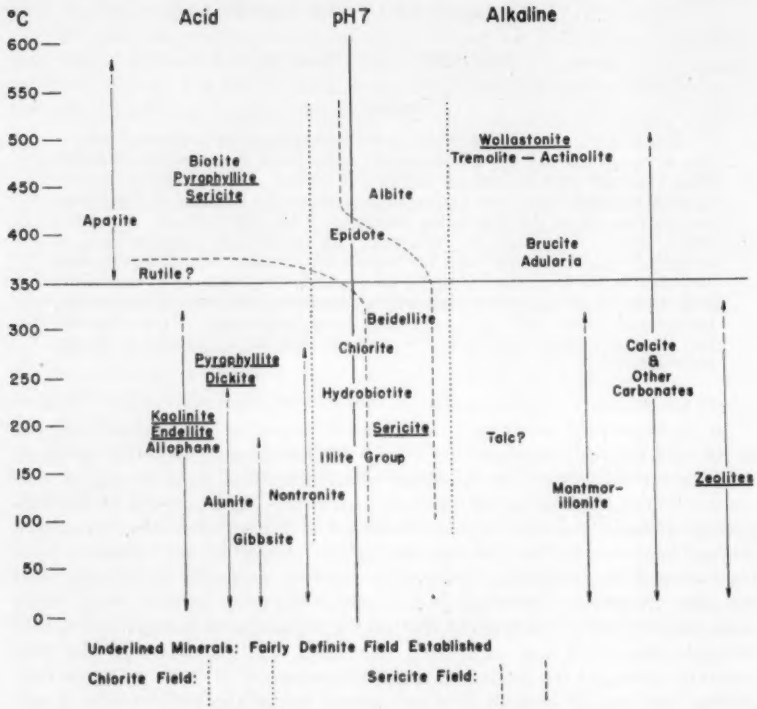
INTRODUCTION.

In hydrothermal alteration studies one of the major problems encountered is the difficulty of identifying accurately the fine-grained minerals involved. This feature alone has been somewhat of a deterrent to those geologists who are not microscopic specialists. In recent years important progress on the fine-grained minerals has been made with the aid of X-ray diffraction, differential thermal analysis, and the electron microscope. Many crystal structures have been worked out eliminating much of the mystery connected particularly with the clay minerals. Although much more work is needed along strict mineralogical lines, it is believed that the identification of fine-grained hydrothermal minerals is now on a fairly firm basis. T. S. Lovering[1] has conveniently arranged the optical characteristics of many of these minerals, thus placing very usable identification procedures before the student who is experienced only in ordinary optical mineralogy. After the minerals have been carefully identified it is necessary to evaluate the data in terms of the physical and chemical conditions under which the respective minerals have formed. Some data on the fields of formation of hydrothermal minerals have accumulated in the literature, but only some of it is good. The monumental task of ferreting out this information for use is sometimes rather discouraging to the non-specialist. In teaching students the fundamentals of hydrothermal alteration at the University of Utah, it was discovered that a chart which incorporates this field of formation data of the hydrothermal minerals was the simplest and clearest way to present the information. It was thought that perhaps this chart, Figure 1, might offer the same advantages to others and it

[1] Lovering, T. S., Rock alteration as a guide to ore, East Tintic District, Utah: Econ. Geol., Mono. I, 1949. Chart in pocket—Optical properties of some secondary minerals.

Fields of Formation of Some Common Hydrothermal Minerals

(Based on Published Information Available to 1951)



is presented here with that idea in mind. The information used for the chart should in no way be construed as representing original work.

SOURCE OF DATA.

Probably the best information on the fields of formation of the different minerals is secured from laboratory experiments where the minerals in question have been synthesized under carefully controlled conditions. To secure this information, many recent publications were examined. For data contained in the older papers, free use was made of the annotated bibliography found in Morey and Ingerson's [2] "The Pneumatolytic and Hydrothermal Alter-

[2] Morey, George W., and Ingerson, Earl, The pneumatolytic and hydrothermal alteration and synthesis of silicates: ECON. GEOL., vol. 32, no. 5 (supplement), pp. 607–761, 1937.

ation and Synthesis of Silicates." The recent experiments of J. W. Gruner [3] and of F. H. Norton [4] proved to be of particular value. A bibliography of all of the papers examined is intentionally omitted from this paper on the grounds that if it was included, the paper would be too voluminous for the purpose for which it is intended. However, some of the more extensive recent papers are listed.[5] The fields of formation of some of the minerals are arrived at primarily through reasoning based upon conditions and associations of their geologic occurrence, as, for example, apatite and tremolite.

EXPLANATION OF CHART.

The ordinate of the chart represents temperature from 0° to 600° C, thus including the field of weathering. A line at 350° C has been drawn which divides the chart into two parts and serves as a convenient reference for two reasons. It is near the critical temperature of water, and 300° to 400° C has been found to be the range in which some important changes take place in laboratory experiments. If a mineral is known to form over a range in temperature a solid arrow is drawn between the temperature extremes, and a dashed arrow is drawn where data is not conclusive.

The abscissa represents pH of depositing solutions in rising values from left to right but only the pH7 line is drawn. The left side of the chart is labeled acid and the right side alkaline and no further definite pH values are given. The fields on either side of pH7 are more or less qualitative in nature in that the distance a mineral is placed from the neutral line is suggestive rather than real. Some of the minerals are underlined indicating that there is fair to good evidence of their particular field of formation while other more doubtful fields bear a question mark. The very important sericite field covers a wide range and is outlined by dashed lines. Very little is known of the chlorite, hydrobiotite, and illite fields, but the best information available at present indicates that they probably form somewhere near neutrality. It will immediately be noticed that many important hydrothermal minerals, such as quartz and pyrite, are missing from the chart. These are believed to have such a wide range in their fields of formation that they are not diagnostic and are therefore intentionally deleted. Minerals usually considered as pneumatolytic, such as tourmaline, idocrase, topaz, etc., also are not included. The chart obviously ignores the effect of pressure but so little quantitative data is known concerning this factor that it was thought best at the present time to leave it out, realizing, of course, that

[3] Gruner, J. W., The hydrothermal alteration of feldspars in acid solutions between 300° and 400° C: ECON. GEOL., vol. 39, no. 8, pp. 578–589, 1944.

[4] Norton, F. H., Accelerated weathering of feldspars: Am. Mineralogist, vol. 22, no. 1, pp. 1–14, 1937.

[5] Lindner, J. L., and Gruner, John W., Action of alkali sulphide solutions on minerals at elevated temperatures: ECON. GEOL., vol. 34, no. 5, pp. 537–560, 1939.

Noll, W., Synthese von montmorilloniten: Chemie der Erde, vol. 10, pp. 129–154, 1936.

Uber die Bildungshedingungen von kaolin, montmorillonit, sericit, pyrophyllit und analcim: Min. pet. Mitt., vol. 48, pp. 210–247, 1936.

O'Neill, Thomas F., The hydrothermal alteration of feldspars at 250 to 400° C: ECON. GEOL., vol. 43, no. 3, pp. 167–180, 1948.

Schwarz, R., and Trageser, G., Uber die synthese des pyrophyllits: Zeitschr. Anorg. Chemie., vol. 225, pp. 142–150, 1935.

minerals forming above 100° C must be under some pressure and those forming at higher temperatures must be under considerable pressure. One other major variable which has been ignored on the chart, and which would effect some of the various fields of formation, is the chemical composition of the depositing media other than pH. For example, if potassium is present, sericite may form in low pH above 350°, while if potassium is absent, pyrophyllite may form instead. The compositional variable, if incorporated in the chart, would so greatly complicate it that its general utility would be lessened.

CONCLUSIONS.

It should be realized that the chart is distinctly limited in its scope and accuracy, and represents simply a summary of the available information to the present date. With the accumulation of new and better established data, the positions of the minerals may change. In this respect, the chart offers a challenge to those who at present have better information and also may perhaps stimulate some students to attack the hydrothermal mineral problem from a laboratory viewpoint. It is expected that the chart will need revision from time to time but just how often changes will be necessary rests chiefly in the hands of the laboratory workers. This tabulation, where first-rate, well understood factors are sifted from more incomplete information, brings forcefully to light the great need for extensive laboratory work on the fields of formation of not only the hydrothermal minerals but on all minerals in general, for minerals are the only observable evidence remaining of the physico-chemical conditions prevailing at the time of their formation and it is only with good information of the above type that the physico-chemical history of the earth will be unraveled.

DEPARTMENT OF MINERALOGY,
UNIVERSITY OF UTAH,
SALT LAKE CITY, UTAH,
May 20, 1952.

CHLORITE–CALCITE PSEUDOMORPHS AFTER ORTHOCLASE PHENOCRYSTS, RAY, ARIZONA.

GEORGE M. SCHWARTZ.

ABSTRACT.

Peculiar dark pseudomorphs after orthoclase phenocrysts occur along fracture zones near the margin of the metallized area at Ray, Arizona. The most intensely altered crystals contain no recognizable orthoclase but consist principally of chlorite and calcite plus small, but variable amounts of sericite, and quartz. Rutile, leucoxene, kaolinite, allophane, hydromica, and sulfides are present in some thin sections.

It is thought that the pseudomorphs were formed by solutions loaded with calcium, magnesium, and iron that moved upward and outward from the ore body where the rocks had been intensely sericitized and the bases other than potassium removed to a considerable degree.

The occurrence emphasizes the problem of the time of alteration. The propylitic stage is often considered to be an early state whereas it probably is often a marginal stage that coincides in time with sericitization, or other alteration, near the center of activity. An expanding sericite-quartz stage of alteration may cause those minerals to invade the propylitic rock and thus furnish evidence of an age difference, but in fact propylitization is probably taking place farther out at the same time.

INTRODUCTION.

In 1945 during a brief visit to Ray, Arizona, in connection with the study of the hydrothermal alteration of the porphyry in disseminated copper deposits,[1] peculiar dark pseudomorphs after orthoclase were noted. A dump of a small shaft shows a profusion of dark phenocrysts in various stages of replacement of orthoclase. A specimen containing these pseudomorphs was collected and on examination in thin section, the pseudomorphs proved to be composed mainly of calcite and chlorite. The occurrence was so unusual that the exposures were revisited in 1946 with H. J. Steele, Geologist of the San Manuel Copper Corporation, to whom I am indebted for assistance in examining the occurrence. More material was collected including both fresh and altered rocks and many orthoclase crystals.

Thin sections and chemical analyses were provided by research funds granted by the Graduate School of the University of Minnesota.

GEOLOGIC SETTING.

The Ray district is located in south central Arizona on the southeast side of the Dripping Springs mountain range and is well described by Ransome.[2]

[1] Schwartz, G. M., Hydrothermal alteration in the "Porphyry Copper" deposits: Econ. Geol., vol. 42, no. 4, pp. 319–352, 1947.

[2] Ransome, F. L., The copper deposits of Ray and Miami, Arizona: U. S. Geol. Survey Prof. Paper 115, p. 62, 1919.

The copper ore deposits are mainly in the Pinal Schist which is intruded by quartz monzonite porphyry and by diabase. Both igneous rocks are also ore-bearing. The ore-bearing rocks have been subjected to considerable hydrothermal alteration as shown by bleaching, innumerable quartz-pyrite veinlets, and disseminated pyrite. The metallized rock is high in sericite and in the igneous rocks this is certainly a hydrothermal mineral, but in the schist it is doubtless of both metamorphic and hydrothermal origin. Analyses quoted by Ransome [3] show a small gain in potash but a notable loss in lime and soda and less conclusively of magnesia.

The pseudomorphs described in this paper occur along a dry wash just west of the town of Ray on the road to Superior. The location is near the letters Trm on plate 45 of the United States Geological Survey Professional Paper 115, at the second bend in the Superior Highway, three-fourths of a mile west of Boyd Heights location and just beyond the general outline of the ore-bearing area, but about four-tenths of a mile west of the caved zone over the Ray ore bodies.

The intrusive in which the phenocrysts occur was named the Teapot Mountain porphyry by Ransome,[4] who described it as a variety of quartz monzonite porphyry. The occurrence here described is at the foot of the south slope of Teapot Mountain.

The fresh rock is conspicuously porphyritic with pink orthoclase phenocrysts ranging up to three centimeters and more in length. The matrix of these large crystals is gray and consists of small phenocrysts of plagioclase, orthoclase, quartz, and biotite in a fine-grained groundmass of quartz and orthoclase. The orthoclase phenocrysts have poikilitic inclusions of euhedral plagioclase and of biotite. Ransome [5] stated that the plagioclase of the Teapot Mountain porphyry was commonly changed to calcite, and sericite and the biotite to chlorite and epidote.

The dark phenocrysts occur on the dump of a small exploration shaft near the bottom of a dry wash, and in a cliff on the north side of the wash near the shaft along a nearly vertical shear zone about 15 feet wide with a strike of N80E. Other less conspicuous fractures cut the porphyry, and show similar alteration to a varying degree. In and near the main fracture zone, and on the dump of the exploration shaft, dark pseudomorphs after orthoclase are abundant and reveal various stages of replacement of the pink orthoclase. In relatively unfractured areas between the main fractures the orthoclase is practically fresh. The groundmass of the porphyry appears little altered in contrast to the orthoclase phenocrysts. This is precisely the opposite of the usual condition in the sericitic and argillic alteration of the copper zones of some porphyry deposits.

About 200 yards west of the highway and on up the wash, good exposures of porphyry occur in which the phenocrysts show no visible alteration in hand specimen. Disintegrated porphyry on the south slope of the wash furnishes an abundance of loose, or easily released, orthoclase crystals which have been little altered, although released from their matrix by desert weathering.

[3] Ransome, op. cit.
[4] ——, op. cit.
[5] Ransome, op. cit.

MICROSCOPIC DESCRIPTION.

Seven thin sections of the phenocrysts were obtained from specimens ranging from apparently fresh orthoclase to dark, almost black, pseudomorphs which seemed to be completely altered. Those which show partial alteration are a mixture of dark gray and pink colors.

A thin-section of a large pink, little altered phenocryst shows that the orthoclase is somewhat clouded with allophane and plagioclase inclusions are altered to sericite. A former biotite inclusion is now a pseudomorph of chlorite and rutile. Quartz inclusions are unaltered, but a small pyrite crystal has altered to iron oxide.

In a thin section of a phenocryst which shows an incipient stage of alteration the poikilitic plagioclase is altered to sericite, quartz, and calcite. Chlorite is scattered throughout the orthoclase. Biotite inclusions, as usual, are altered to sericite, chlorite, and rutile, and orthoclase is somewhat clouded with allophane. The scarcity of calcite in the incipient stage suggests that it was formed during a late stage of the alteration.

The dark pseudomorphs consist mainly of coarse calcite and chlorite (Nm 1.63), which, in part, shows well developed spherulitic texture and an intense ultrablue color in polarized light. A very little pyrite, chalcopyrite, and bornite occurs with the other alteration products, and orthoclase remnants are veined by calcite. Biotite inclusions have altered completely to chlorite, sericite, and rutile, and several plagioclase inclusions are now pseudomorphs consisting of sericite, calcite, and chlorite. One thin section shows a concentration of spherulitic chlorite at the center of the crystal with the remainder largely calcite, and shadows of replaced euhedral plagioclase inclusions remain in the calcite, which also contains some disseminated chlorite.

One greenish phenocryst contains considerable orthoclase as remnants in calcite and chlorite, and pseudomorphs after euhedral biotite inclusions consist of sericite, hydromica, rutile, and chlorite. The orthoclase remnants are clouded with allophane and small pyrite crystals have altered to iron oxide.

Along some of the shear zones pseudomorphs are light gray and have an obvious foliation. A thin section reveals complete alteration to sericite, hydromuscovite, nontronite, and quartz with the micaceous minerals well oriented. There is doubt about the relation of this alteration to that in which calcite and chlorite is dominant, but sericite preceded the shearing; whereas, the chlorite and calcite are probably later and affected larger volumes of rock.

One thin section shows a part of a dark green phenocryst embedded in the matrix. The phenocryst is composed mainly of coarse calcite with numerous inclusions of chlorite and remnants of orthoclase. Former plagioclase inclusions are represented by sericite patches, and small biotite phenocrysts in the groundmass have altered completely to colorless mica and chlorite with inclusions of rutile. The groundmass is not highly altered, but sericite and kaolinite are disseminated throughout, and some of the plagioclase grains of the groundmass have largely escaped alteration in contrast to the almost complete alteration of the large orthoclase phenocryst.

CHEMICAL CHANGES.

It is evident from the mineral composition that there has been a pronounced chemical change during the alteration of the orthoclase phenocrysts. Some of the changes, however, are not readily inferred from the mineral composition, for example, the relative amount of magnesium and iron added to the fresh phenocrysts to form chlorite. It was, therefore, decided to obtain complete chemical analyses of phenocrysts of orthoclase and the pseudomorphs of the phenocrysts.

For analysis two typical fresh and two altered phenocrysts were selected, and each face of the crystals was ground on a glass plate with carborundum

TABLE 1.

CHEMICAL ANALYSES OF FRESH AND ALTERED PHENOCRYSTS.

	Percentage		Grams in 100 cc of rock		Increase or decrease in grams per 100 cc	Percent of change
	1	2	1	2		
SiO_2	63.36	40.11	157.51	108.42	−49.09	−31.1
Al_2O_3	19.33	15.41	48.05	41.65	− 6.40	−13.3
Fe_2O_3	.24	.51	.60	1.38	+ .78	+13.0
FeO	.27	7.16	.67	19.35	+18.68	+2788.
MgO	.13	3.12	.32	8.43	+ 8.11	+ 253.
CaO	.18	12.13	.45	32.79	+32.34	+7182.
Na_2O	1.73	.45	4.30	1.22	− 3.08	− 71.6
K_2O	12.79	7.31	31.80	19.76	−12.04	− 37.9
H_2O+	.51	2.92	1.27	7.89	+ 6.62	+ 521.
H_2O-	.08	.10	0.20	.27	+ .27	0.
CO_2	.04	9.96	.10	26.92	+26.82	
TiO_2	.06	.10	.15	.27	+ .12	
P_2O_5	.03	.03	.07	.08	+ .01	
MnO	.01	.30	.03	.08	+ .05	
SrO	.10	.05	.27	.13	− .14	
BaO	.96	.45	2.38	1.22	− 1.16	
FeS_2	.00	.06		.16	+ .16	
Total	99.82	100.17				

1. Orthoclase crystals from Teapot Dome porphyry, Ray, Arizona. J. A. Maxwell, Analyst. Grain density 2.580; bulk density 2.486; porosity 3.6 percent.

2. Pseudormorphs after orthoclase crystals from the Teapot Dome porphyry, Ray, Arizona. J. A. Maxwell, Analyst. Grain density 2.723; bulk density 2.703; porosity 0.7 percent.

powder to remove impurities clinging to the surfaces. Because the phenocrysts are relatively small it was impracticable to make thin sections of the crystals to be analyzed. The results indicate that the orthoclase phenocrysts were about as unaltered as any that could be selected. The pseudomorphs, however, proved to contain much more residual orthoclase than indicated by some of the thin sections of other pseudomorphs. The alteration and chemical changes indicated are, therefore, not extreme but less than might have been obtained from more thoroughly altered specimens. There is every reason to believe that the results are typical. The bulk density of each phenocryst was determined previous to grinding for grain density determination and analysis.

As would be expected from the mineral changes shown by the thin sections of fresh and altered phenocrysts there has been an important addition of ferrous iron, lime, magnesia, carbon dioxide, and water. The additions have been balanced by a decrease in potassa, silica, and, to a lesser extent of alumina and soda. The gains and losses are shown graphically by Figure 1. In terms of absolute amounts silica shows a loss of 49 grams per 100 cubic centimeters of original mineral or a percentage loss of 31.1 percent. This loss contrasts with an increase in silica in the ore and protore of the Ray district as shown by Ransome.[6]

The loss of potash is also in contrast to the alteration in and near the Ray ore bodies where the rocks contain somewhat more potash than unaltered rocks nearby, but both are high in sericite.

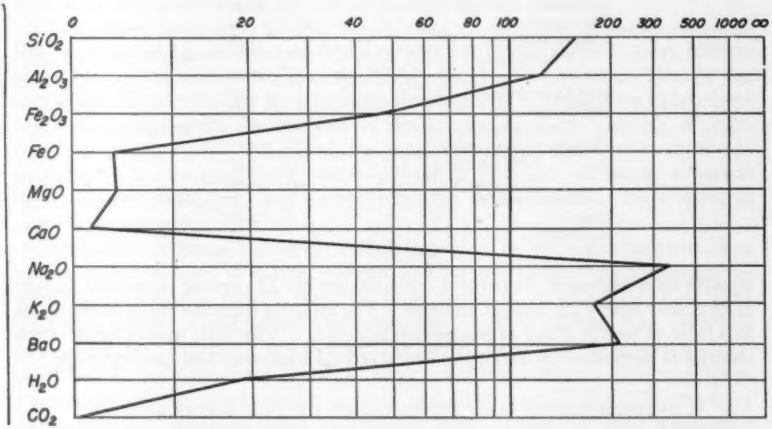


FIG. 1. Straight-line diagram representing the gains and losses in the alteration of orthoclase phenocrysts to pseudomorphs.

The large increase in ferrous iron is particularly significant as practically all of this gain must be represented by iron in chlorite. In the ore of the Ray district ferrous iron, except that in pyrite, is low indicating destruction of the ferromagnesian minerals.

Calculations based on the chemical analyses give a good idea of the probable mineral composition of the fresh and altered phenocrysts (Table 2). Thin sections show only very small amounts of plagioclase as inclusions in the orthoclase crystals. It therefore follows that the orthoclase contains sodium roughly equivalent to 14.6 percent albite. Barium is also surprisingly abundant. Total calculated feldspar equals 93.5 percent. The other 6.5 percent consists of original inclusions and alteration products. In contrast the altered phenocrysts

[6] Ransome, op. cit., pp. 136, 159.

TABLE 2.

CALCULATED MINERAL COMPOSITION. (SOME MINOR CONSTITUENTS OMITTED.)

Two orthoclase phenocrysts combined

	Percent	
Orthoclase molecule	75.68	
Albite molecule	14.66	
Celsian molecule	2.35	
Anorthite molecule	.80	
Kaolinite (allophane)	4.10	
Quartz	1.33	
	98.92	

Two pseudomorphs after orthoclase phenocrysts combined

	Percent	
Orthoclase molecule	43.26	
Albite molecule	3.81	
Celsian molecule	1.10	
Total feldspar		48.17
Calcite	21.66	
$MnCO_3$ molecule	.49	
$FeCO_3$ molecule	.63	
Total carbonate		22.78
Chlorite, $H_4Fe_2Al_2SiO_9$	16.11	
$H_4Mg_2Al_2SiO_9$	4.66	
$H_4Mg_2Si_2O_9$	4.25	
Total chlorite		25.02
Quartz	3.50	
Hematite	.51	

contain approximately 48 percent feldspar, nearly 23 percent carbonate largely calcite, and nearly 25 percent chlorite. The chlorite contains the iron molecule in a ratio of nearly 2 to 1 of magnesian molecule. The high iron content of the chlorite is suggested by the index which is 1.63 with very low birefringence.

INTERPRETATION AND SIGNIFICANCE OF THE PSEUDOMORPHS AFTER ORTHOCLASE.

It is well known that orthoclase is generally more resistant to hydrothermal alteration than plagioclase, and other common silicates such as biotite and hornblende. Often this is accounted for by the fact that the solutions were carrying potassium and commonly form sericite or secondary orthoclase rather than attacking the rock orthoclase. Even in argillic alteration where the solutions are acidic, the plagioclase alters easily, and orthoclase is relatively stable. It is, therefore, somewhat surprising to find orthoclase so intensely altered that crystals ranging up to an inch in length have been changed to pseudomorphs.

Chemical data show that calcium is to a large degree removed in the zone of intense sericitization of many disseminated copper desposits. In view of the location of the occurrence of the altered phenocrysts along shear zones near and above the Ray ore body, it seems that an explanation of the alteration is available. The locus of most intense alteration, and perhaps the main source of solutions, lies beneath and within the area of the ore body. As the solutions sericitized the schist and porphyry, potassium was deposited, and calcium and

other bases were dissolved. Ransome's [7] analyses of the hydrothermally altered rocks from the Ray district show very low lime, magnesium, and relatively high potassium.

As the solutions moved outward and upward, they doubtless travelled mainly along shear zones such as those described above. The solutions after leaving the ore body were probably deficient in potassium, relatively high in calcium, magnesium, and iron, and presumably became cooler as they moved away from the main area of concentration. Conditions then favored the destruction of orthoclase and the deposition of calcium, and to a considerable extent of magnesium and ferrous iron, as shown by the development of much chlorite.

It has long been known that zones of propylitic alteration often form the borders of areas of intense sericitization and it is probable that an explanation similar to that given above applies to these propylitic borders.

The writer has found at the San Manuel exploration, 25 miles south of Ray, that calcium is almost completely removed from the zones of more intense alteration. On the north side of the highly alterated area at San Manuel the fading out is accompanied by a striking development of epidote and zoistite in plagioclase and biotite phenocrysts of the porphyry. Low calcium is characteristic of the highly sericitized ore zones but calcite veins make their appearance in the hanging wall, where alteration is weak. It seems a logical deduction that the calcite was formed from the calcium leached from the area of intense alteration.

At Bisbee, Arizona, the writer found that dikes in the limestone have often been intensely altered to calcite, epidote, and zoisite. There the hydrothermal solutions necessarily passed through large amounts of limestone, and were doubtless robbed of potassium and loaded with calcium which they promptly exchanged for potassium on entering the porphyry. It is noteworthy, however, that in the Sacramento stock at Bisbee sericitic alteration is conspicuous. Presumably the hydrothermal solutions travelled upward through porphyry and schist and therefore were not loaded with calcium as they were after travelling through limestone to reach the dikes and sills.

Peterson [8] has described the alteration in detail for the Castle Dome deposit of the Miami district where a weak prophylitic alteration is marginal to a clay and a clay sericite phase of alteration, and there too it seems possible that the solutions had dissolved magnesium, ferrous iron, and calcium from the zone of intense alteration and thus caused a propylitic alteration as they worked outward.

In zones of marginal alteration the formation of chlorite in plagioclase feldspar is common. In a sense, this is puzzling because neither magnesium nor ferrous iron are available in the plagioclase. Both, however, may be derived from the destruction of biotite and other minerals in zones of more intense argillic and sericitic alteration, where the ferromagnesium minerals

[7] Ransome, op. cit.

[8] Peterson, Nels P., Hydrothermal alteration in the Castle Dome copper deposit: ECON. GEOL., vol. 41, no. 8, pp. 820–840, 1946.

may be almost completely removed as is the case in several disseminated copper deposits.

The occurrence at Ray suggests that peripheral areas of ore bodies or zones of alteration, are worthy of particularly careful study for evidence of precipitation of elements dissolved in the area of more intense alteration. The striking occurrence here described shows that such evidence may be easily overlooked as it has been in other districts studied by the writer.

The occurrence at Ray also emphasized the problem of the time of alteration. The propylitic stage is often considered to be an early stage of alteration, but according to the inferences drawn above, the calcite-chlorite alteration is actually of the same age as the intense sericite-quartz-pyrite alteration of the Ray ore bodies. If the alteration spreads as it develops, the sericite-quartz-pyrite zone may invade the marginal zone and there give definite evidence that it is later. This suggests the desirability of considering the whole alteration as dynamic, rather than static, as indicated by conditions now exposed to view. In this respect the process is in accord with the conclusions of Sales and Meyer [9] based on studies at Butte.

UNIVERSITY OF MINNESOTA,
MINNEAPOLIS 14, MINN.,
April 17, 1952.

[9] Sales, Reno H., and Meyer, Charles, Wall rock alteration at Butte, Montana: Am. Inst. Min. Eng. Trans., vol. 178, pp. 9–35, 1948.

DISCUSSIONS

ALPINE LEAD–ZINC ORES OF EUROPE.

Sir: In reply to the criticism of the article "Alpine lead-zinc ores of Europe" by F. Gordon Smith in ECONOMIC GEOLOGY, vol. 47, pp. 347–349, May, 1952, the writer would like to make the following statements:

1. The treatment of pH arose from a desire to state in simplest terms the essentials of the argument presented. Neutrality, for the purposes of the paper, was defined at pH = 7. The notation OH_3^+ was used for the hydrogen ion because according to Bronsted[1] the hydrogen is hydrated to form the oxonium ion (H_3O^+ or OH^+_3) and the concentration of unhydrated H^+ even in an acid solution is about 10^{-150}, which is negligible.

2. The instability of wurtzite is relative as Smith has indicated. However, that wurtzite is much more likely to form in acid than in alkaline solutions is indicated in the experiments of Allen and Crenshaw.[2]

3. The writer wishes to refute categorically the statement that the fact that wurtzite was crystallized in strongly alkaline solutions in Smith's experiments [3] was withheld. In fact, the writer has clearly stated the exact order of crystallization found in Smith's experiments with the notation that the experiments were performed "on the alkaline side." [4]

4. The solubility of calcium carbonate has been treated at length in a recent article by Garrels and Dreyer.[5] This work also partly substantiates the conclusions reached by Jicha on theoretical grounds with experimental data. For other data on the solubility of calcium carbonate the reader is referred to Seidell.[6]

5. The conclusions advanced by the writer were admittedly somewhat speculative and were based on the premise that the argument advanced was an accurate analysis of the prevailing conditions as given in the descriptive part of the article. No pretense was made as to the experimental accuracy of the conclusions and the conclusions reached were those which seemed most

[1] Bronsted, J. N., Chem. Rev., vol. 5, pp. 285, 239–240, 1926.

[2] Allen, E. T., and Crenshaw, J. L., The sulfides of zinc, cadmium, and mercury; their crystalline forms and genetic conditions: Am. Jour. Sci., 4th ser., vol. 34, pp. 341–396, 1912.

[3] Smith, F. Gordon, Solution and precipitation of lead and zinc sulfides in sodium sulfide solution: ECON. GEOL., vol. 35, no. 5, pp. 646–658, 1940.

[4] Jicha, H. L., Jr., Alpine lead-zinc ores of Europe: ECON. GEOL., vol. 46, no. 7, pp. 707–725, 1951.

[5] Garrels, R. M., and Dreyer, R. M., Mechanism of limestone replacement at low temperatures and pressures: Geol. Soc. America Bull., vol. 63, no. 4, pp. 325–379, 1952.

[6] Seidell, Atherton, Solubilities of inorganic and metal organic compounds, 3rd ed., vol. 1, pp. 264–276, D. Van Nostrand and Co., New York, 1940.

reasonable from the available evidence. The writer has pointed out that other possibilities exist but finds it difficult to reconcile the ease with which the pertinent chemical data fit the acid solution theory to a conclusion in favor of alkaline solutions.

HENRY L. JICHA, JR.

NEW MEXICO BUREAU OF MINES
AND MINERAL RESOURCES,
SOCORRO, NEW MEXICO,
July 10, 1952.

REVIEWS

Principles of Petroleum Geology. By E. N. Tiratsoo. Pp. 449; figs. 115. McGraw-Hill Book Co., Inc., New York, and Methuen & Co., Ltd., London, 1952. Price, $7.50.

This is the second book to appear recently under the identical title from the same publisher. W. L. Russell's book preceded it by less than a year. This book was written as a textbook for Honours students at the Royal School of Mines in England. The general plan of the work is to discuss first the principles of origin, accumulation, and migration, followed by illustrations of these principles by discussion of the chief oilfields of the world, arranged by continents. From this factual information descriptions are given of the ways future oil pools may be discovered both by surface and subsurface methods. The first 4 chapters on introduction and principles cover 90 pages; descriptions of fields cover 190 pages. Chapter 5 treats of the geologic and geographic distribution of oil fields. Chapters 11 and 12 deal with surface indications and surface oil-finding; Chapter 13 with geophysics; Chapter 14 with exploration geology; Chapter 15 with drilling mud; and Chapter 16 with methods of correlation, including paleontology and mineral analysis and identification.

Bibliographies follow the end of each chapter but, rather surprisingly, the references, as well as all of the statistical data, end with 1946. In consequence, the valuable contributions of late years, such as are found in the two recent American textbooks, are lacking. Reef traps or bioherms are not mentioned, and it is stated that "About 96 percent of Canadian (oil) production has come from the Turner Valley field. . . ." This is an example of many similar statements that might have been correct 6 to 10 years ago, but are out of place in a book published in 1952. The reader cannot but wonder why, if a book merited publication, that it could not have been brought up to date before publication. An occasional inset reference to a few developments in 1946 or 1947 do not bring a book up to date. A revised second edition was needed before the first edition appeared.

The book is rather lightly illustrated for one dealing with petroleum geology, but the descriptions of European and Asian fields are more complete than those found in American textbooks. This book will suffer considerably in comparison with the recent and up-to-date textbooks by W. L. Russell and K. K. Landes.

Imperfections in Nearly Perfect Crystals. Edited by W. Shockley (Chairman), J. H. Hollomon, R. Maurer, and F. Seitz. Pp. 490; figs. 175. John Wiley & Son, Inc., New York, 1952. Price, $7.50.

This volume grew out of a meeting at Pocono Manor, Pennsylvania, in 1950, of scientists from universities, industry, and government laboratories to discuss imperfections in crystals. It is sponsored by the Committee on Solids, Division of Physical Sciences of the Natural Research Council. Under the chairmanship of Dr. Shockley the material of the symposium and additional material have been assembled into 17 chapters by 20 distinguished authors.

The work is divided into 4 parts: I, On the Nature of Imperfections in Nearly Perfect Crystals; II, Role of Imperfections in Deformation; III, Diffusion and Related Phenomena; IV, The Properties and Effects of External and Internal Surfaces of Crystals. The book is a fundamental study of crystal structure, crystal growth, substructures, slippage, and diffusion. It thus brings together in one volume a mass of principles and details of crystals and crystal growth, and as such should be of great interest to crystallographers and metallurgists.

Panorama of Science, 1952, Annual Supplement to the Smithsonian Series for 1952. Compiled and Edited by Webster Prentiss True. Pp. 422; figs. 97. The Series Publishers, Inc., New York, 1952.

This volume is an annual supplement to the Smithsonian series on the natural sciences, being preceded by 12 volumes written by scientists of the Smithsonian Institution. For this volume there have been selected 27 articles that have appeared during 1951 in various scientific and nonscientific journals and magazines. The articles selected are mainly short ones written in non-technical or easily understandable language that cover the various fields of learning in which new knowledge is appearing. They deal with pre-history, astronomy; electronics, atomic, physics; chemistry, geology, biology, agriculture, medical phases, meteorology, cultural, and general.

The titles of the included articles and the authors are: Science and Human Affairs, by E. C. Stakman; Today's Astronomical Frontiers, by O. Struve; The Origin of the Solar System, by H. S. Jones; Power from the Atom—An Appraisal, by C. G. Suits; Some Prospects in the Field of Electronics, by V. K. Zworykin; Some Results in the Field of High-Pressure Physics, by P. W. Bridgman; Chemistry in the Twentieth Century, by H. C. Urey; Pin-Pointing the Past with the Cosmic Clock, by R. F. Flint; A Résumé of Researches at the Arizona Meteorite Crater, by H. H. Nininger; The Canadian Meteor Crater, by V. B. Meen; Atmospheric Control, by W. J. Kotsch; Hurricanes of the 1950 Season, by G. Norton; Origin of Life on the Galapagos Islands, by K. W. Vinton; Navigation in Birds, by G. V. T. Matthews; Guayule—An American Source of Rubber, by K. W. Taylor; Food, Agriculture and Health, by C. G. King; Motion Sickness, by D. B. Crowl; Some Basic Principles in Chinese Culture, by A. W. Hummel; The Inter-Agency Archaeological Salvage Program in the United States, by F. Johnson; New Light on Ancient America, by R. Linton; Dioramas and Archaeology, by A. Spoehr; Future Uses of Solar Energy, by M. Telkes; Improving the Position of Electricity as Primary Energy for Space Heating, by C. Frere; The Hypothesis of Cybernetics, by J. O. Wisdom; Operations Research, by P. M. Morse; Predictions; Science and Civilization, by R. R. Williams.

This careful selection will give the lay reader and the scientist an opportunity to learn what is going on in fields of thought outside of his own interests.

Geology. By O. D. von Engeln and Kenneth E. Caster. Pp. 730. McGraw-Hill Book Company, Inc., New York, 1952. Price, $7.00.

This textbook of geology is a bit different from most elementary textbooks, chiefly in the order of treatment. First, it is divided about 2/3 to physical geology and 1/3 to historical geology. Secondly, the plan is to lead the student from the known to the unknown, although this hardly holds in the physical geology where magmas and intrusives come before sedimentation or weathering. Thirdly, the

historical geology is completely reversed from most textbooks. It starts with The Pleistocene Glacial Epoch under which glaciers and glacier action are treated, and then comes The Glacial Epoch and Man, The Geologic Record, and The Tertiary. These follow the Mesozoic and Paleozoic Eras and the Cryptozoic Eon, which includes The Precambrian, The Interior of the Earth, and The Age and Origin of the Earth. Thus, the student is led into the more and more remote geologic past with the most speculative and remote at the very end of the book. It will be seen that there is some admixture of what customarily is taken up under physical geology, in with historical geology. This is logical and to the good.

The physical geology contains much of the customary content of elementary textbooks. It is divided into 3 parts—Introduction, including Materials of the Earth, and History of Geologic Ideas; The Natural History of Igneous Rocks, including magmas, intrusion and extrusion, volcanism, igneous rocks, and weathering of igneous rocks; and Structure, Process, Forms, including sedimentation, underground water, diastrophism, structure, metamorphism, mountains, sculpturing, oceans, and glaciers.

Throughout, groups of questions are interspersed and each chapter is concluded with a bit of supplementary readings. The book is abundantly and well illustrated. Technical terms first introduced are placed in italics, and Latin and Greek terms used, particularly under historical geology, are followed in parentheses by the meaning of the term. The book is thoughtfully organized, skillfully written, and well proves a strong competitor to existing elementary textbooks of geology.

Journal of Research into the Geology and Natural History of the Various Countries Visited by H.M.S. Beagle. By CHARLES DARWIN. A facsimile reprint of first edition, 1839. Pp. 615; pls. 16. Hafner Publishing Co., New York, 1952. Price, $7.50.

This classical book gives some of the fundamental information that gave rise to Darwin's famed Origin of Species and Descent of Man. If Darwin had not become so rightly famous for the last two books he would become more famous for this Voyage of the Beagle. Here is given the keen observations of a young geologist of 25 years, after a 5-year voyage around the world in the Beagle. The original book became famous as an example of objective observations of countries, seas, people, nature, and geologic and biological phenomena—factual data that formed the basis for theories of evolution and the origin of land forms. An appendix gives some later expansions and corrections to statements made in various chapters.

Too few people have read the original book. This facsimile reprint now gives opportunity to any lay reader and scientist to fill a loophole in his fund of knowledge.

BOOKS RECEIVED.

H. R. TREMAINE.

U. S. Geological Survey—Washington, D. C., 1952.

Circ. 183. Water Resources of the Detroit Area, Michigan. C. O. WISLER, G. J. STRAMEL, AND L. B. LAIRD. Pp. 36; figs. 30; tbls. 9; pls. 4. *Description of area, climate, ground water, water-bearing formations, water supplies, potentialities, water laws, and references.*

Circ. 185. Reconnaissance for Radioactive Deposits along the Upper Porcupine and Lower Coleen Rivers, Northeastern Alaska. MAX G. WHITE. Pp. 12; figs. 3; tbls. 3. *Geology, investigations, sedimentary rocks, with some detailed data.*

Review of Airborne Radioactivity Survey Techniques in the Colorado Plateau. J. A. TAVELLI. Pp. 12. U. S. Atomic Energy Comm., Rmo-697, Oak Ridge, Tenn., 1951. Price, 10 cts. *Definition of airborne prospecting, instrumentation, operational techniques, specific operations—Colorado Plateau, and results of operations.*

Proceedings of the Pan-American Congress on Prehistory, 1947. EDITED BY L. S. B. LEAKEY AND SONIA COLE. Pp. 239; figs.; tbls. Philosophical Library, New York, 1952. Price, $8.75. *In 3 sections—I, geology, general paleontology, climatology, with special reference bearing on African prehistory; II, human paleontology; III, prehistorical archaeology.*

Natal Regional Survey, Vol. I, Archaeology and Natural Resources of Natal. Pp. 140; figs. 22; charts 10; photos. 24. Oxford University Press, London, 1952. *Archaeology, geology, physiography, climate, vegetation, timber, soils, fauna, and water resources.*

Illustrated Key to West North American Gastropod Genera. A. MYRA KEEN AND JOHN C. PEARSON. Pp. 39; figs. Stanford University Press, Stanford Calif., 1952. Price, $1.50. *A new key to representative groups of marine gastropod mollusks (snails and slugs) found from San Diego to Alaska. 240 Pacific Coast molluscan genera are covered. Explanation of how key is to be used, a glossary of terms, an alphabetical index, and a systematic index.*

California Division of Mines—San Francisco, 1946, 1948, 1950–52.

Special Rept. 19. Geology and Ceramic Properties of the Ione Formation, Buena Vista Area, Amador County, California. JOSEPH A. PASK AND MORT D. TURNER. Pp. 39; figs. 24; pls. 4. *Methods of investigation, application of differential thermal analysis to clay mineralogy, descriptive geology, geologic history, economic geology, value of ceramic test in geologic investigation, and a selected bibliography.*

Bull. 134, Pt. I, Chpt. 1. Geological Investigations of Chromite in California. FRANCIS G. WELLS, FRED W. CATER, JR., AND GARN A. RYNEARSON. Pp. 76; figs. 9; tbls. 6; pls. 10. *Klamath mountains—chromite deposits of Del Norte County, California.*

Bull. 134, Pt. I, Chpt. 2. Geological Investigations of Chromite in California. FRANCIS G. WELLS AND FRED W. CATER, JR. Pp. 50; figs. 4; tbls. 7; pls. 3. *Klamath mountains—chromite deposits of Siskiyou County, California.*

Bull. 134, Pt. II, Chpt. 1. Geological Investigations of Chromite in California. D. H. DOW AND T. P. THAYER. Pp. 38; figs. 2. *Coast ranges—chromite, deposits of the northern coast ranges of California.*

Bull. 134, Pt. III, Chpt. 1. Geological Investigations of Chromite in California. FRED W. CATER, JR. Pp. 32; fig. 1; tbl. 1; pl. 1. *Sierra Nevada —chromite deposits of Tuolumne and Mariposa Counties, California.*

Bull. 134, Pt. III, Chpt. 2. Geological Investigations of Chromite in California. FRED W. CATER, JR. Pp. 25; fig. 1; tbl. 1; pl. 1. *Sierra Nevada —chromite deposits of Calaveras and Amador Counties, California.*

Bull. 134, Pt. III, Chpt. 3. Geological Investigations of Chromite in California. GARN A. RYNEARSON. Pp. 43; figs. 7; tbls. 4; pls. 2. *Sierra Nevada—chromite deposits of Tulare and Eastern Fresno Counties, California.*

Bull. 134, Pt. III, Chpt. 4. Geological Investigations of Chromite in California. FRED W. CATER, JR., GARN A. RYNEARSON, AND DONALD H. DOW. Pp. 59; figs. 6; tbls. 4; pls. 8. *Sierra Nevada—chromite deposits of El Dorado County, California.*

Bull. 161. Geology of the Healdsburg Quadrangle, California. WILLIAM KELSO GEALEY. Pp. 76; figs. 3; pls. 8. *Including chapter on Mineralogy of the California Glaucophane Schists, by George Switzer.*

California Journal of Mines and Geology, Vol. 48, No. 3, July 1952. Pp 68; fig. 1; pls. 6. *3 chapters, 1, California Talc in the Paint Industry, by Richard S. Lamar; 2, Geology of the Starbright Tungsten Mine, San Bernardino County, California, by George C. Hazenbush; 3, Mines and Mineral Resources of Merced County, by Fenelon F. Davis and Denton W. Carlson.*

Ohio Geological Survey—Columbus, 1951–52.

Rept. Inv. 14. The Pittsburgh Coal of the Federal Creek Field with Notes on the Surface Geology of Ames Township, Athens County, Ohio. GILBERT E. SMITH. Pp. 13; figs. 5; tbls. 2; pls. 4. *Geology of Ames Township and Reserves of Federal Creek Coal Field.*

Inf. Circ. 7. JOHN H. MELVIN. Pp. 14; figs. 7. *Annual report.*

Pennsylvania Topographic and Geologic Survey—Harrisburg, 1951–52.

Inf. Cicr. 2. Industrial Minerals in Pennsylvania in 1951. ROBERT C. STEPHENSON. Pp. 6. *Some of the significant trends and developments during 1951 in the widely diversified field of industrial mineral production in Pennsylvania are related.*

Progress Rept. 139. Oil and Gas Developments in Pennsylvania in 1951. CHAS. R. FETTKE. Pp. 20; figs. 4; tbls. 3; pls. 2. *Deep-sand developments, shallow-sand developments, and oil and gas production.*

The Stratigraphy and Trilobite Faunas of the Cambrian Sedimentary Rocks of Cape Bretton Island, Nova Scotia. R. D. HUTCHINSON. Pp. 124; figs. 3; pls. 7. Canada Dept. Mines Geol. Survey Mem. 263, Ottawa, 1952. Price, 75 cts. *Detailed account of the succession and distribution of the Cambrian formations, and outlines the probable history of the island during Cambrian time. Discussion of the faunas is given, and all trilobite fossils found in them are described and illustrated.*

Manitoba Department of Mines and Natural Resources—Winnipeg, 1952.

Pub. 49–6. Structural Studies of the Long Lake-Halfway Lake Area, Rice Lake Mining Division. G. A. RUSSELL. Pp. 10; geologic map. *General geology, geologic history of the area, structural geology, and economic geology.*

Pub. 51–4. Geology of the Utik Lake-Bear Lake Area, Oxford Lake Mining Division, Northern Manitoba. G. C. MILLIGAN. Pp. 24; fig. 1; tbl. 1; geologic map. *General geology, sedimentary rocks, granitic rocks, structure, geologic history, and economic geology.*

Great Britain Department of Scientific and Industrial Research—London, 1952.

Mem. Vol. IV. Fluorspar. K. C. DUNHAM. Pp. 143; figs. 11; pls. 4. *General introduction, West Durham and adjacent areas, Northwest Yorkshire, North Derbyshire, Cornwall and Devon, and Scotland.*

Rept. GSM/AED. 95. The Albite-Riebeckite-Granites of Nigeria. R. A. MACKAY AND K. E. BEER. Pp. 25; maps 8. Atomic Energy Division. *Occurrences of Albite-Riebeckite-Granite, procedure, general geology and previous literature, detailed geology and radiometry, and conclusions.*

Rept. GSM/AED. 116. The Petrography of some of the Riebeckite-Granites of Nigeria. K. E. BEER. Pp. 38; maps 6. Atomic Energy Division. *General geology of the Northern Tinfield, the petrographic province of Northern Nigeria and adjoining territories, detailed petrology and geology of the Riebeckite-Granites, mineralogy of the granites, chemical considerations, and conclusions.*

Report on the Geological Survey Department for the Financial Year 1950–51. Pp. 8. Government Printing Department, Accra, Gold Coast, 1952. Price, 2s. 6d.

Report of the Government Chemical Laboratories for the Year 1949. Pp. 40. Geol. Survey of Western Australia, Perth, 1951. *Extract from the Mines Department Annual Report.*

Minerales No. 40. Pp. 36; fig. 1. Inst. ing. Chile Rev., Santiago, 1952. *Includes further data on copper in Chile.*

Ministerio de Minas e Hidrocarburos—Caracas, Venezuela, 1952.

Bol. 76. Actividades Petroleras. Pp. 16.

Bol. 78. Actividades Petroleras. Pp. 16.

Escuela Nacional de Ingenieros—Lima, Perụ, 1951–52.

Bol. Ser. IV, T. 24. CONTRIBUTIONS BY JOSÉ ARRISUENO ARISPE AND CÉSAR SOTILLO P. Pp. 44.

Bol. Ser. IV, T. 25. CONTRIBUTIONS BY JAVIER DÍAZ CHÁVEZ AND DANIEL ESCOBAR E. Pp. 83.

Comité Special du Katanga—Bruxelles, 1950.

Vol. II, T. 1. TRAVAUX DE LA COMMISSION GÉOGRAPHIQUE ET GÉOLOGIQUE. Pp. 276; illusts. Comptes rendus du Congrès Scientifique, Élisabethville, 1950. *Two great historic eras of the geology of Katanga and the continents of the southern hemisphere; history of the continent of Gondwana; table of formations of Katanga and their characteristics; a comparison of the socle of Katanga with that of Africa.*

Vol. II, T. 2. TRAVAUX DE LA COMMISSION GÉOGRAPHIQUE ET GÉOLOGIQUE. Pp. 221; illusts. Comptes rendus du Congrès Scientifique, Élisabethville, 1950.

Geologia e Jazigos de Chumbo e Zinco da Beira Baixa. DÉCIO THADEU. Pp. 144; illusts. Soc. Geol. de Portugal, Porto, 1951.

Zentralblatt für Geologie und Paläontologie. O. H. SCHINDEWOLF AND M. SCHWARZBACH. Pp. 255. E. Schweizerbart'sche Verlagsbuchhandlung, Stuttgart, 1951.

Genetische Lagersättengliederung auf geotektonischer Grundlage. HANS SCHNEIDERHÖHN. Pp. 89; map 1. E. Schweizerbart'sche Verlagsbuchhandlung, Stuttgart, 1952.

Geologie. F. LEUTWEIN. Pp. 142; figs. 45. Akademie-Verlag, Berlin, 1952.

Annales de la Société Géologique de Pologne, Vol. XXI, Fasc. 1. Pp. 124. Cracow, 1952.

Pp. 227; illusts. Muséum d'Histoire Naturelle du Pays Serbe, Ser. A, Livre 4, Belgrade, 1951.

Pp. 152. National Science Museum, Bull. 31, Ueno Park, Tokyo, 1952. *Includes a synoptical sketch of Korean flora, by Takenoshin Nakai.*

SOCIETY OF ECONOMIC GEOLOGISTS

PRELIMINARY ANNOUNCEMENT.

The Society of Economic Geologists is continuing its practice of meeting alternately with the Geological Society of America and the American Institute of Mining and Metallurgical Engineers. The November meeting with the GSA at Boston will be an informal meeting for which a limited program has already been completed. In addition the Society will sponsor a cocktail party at the Boston meeting.

The next Annual Meeting of the Society of Economic Geologists will be held jointly with the AIME in Los Angeles, California, during the period February 16–19, 1953. Plans are being made for a technical program comprising five or six half day sessions, two or three of them to be organized in collaboration with the AIME.

It is the consensus of the Program Committee that increased emphasis should be placed upon fewer and better papers, stricter enforcement of time allotments during presentation of these papers, and upon more informal discussion from the floor. Moreover, we hope that most of the papers that are offered for presentation will deal with subjects that lie within one of the major fields listed below. The sessions currently planned are as follows:

1. Geology of the so-called rare industrial minerals (joint session with AIME)
2. Geology of dimension stones (joint session with AIME)
3. Mineral deposits of the Southwest (two sessions)
4. Miscellaneous topics (one session)
5. Panel discussion on nature and derivation of ore-forming fluids.

All authors who plan to give papers at the 1953 meeting are urged to submit titles and abstracts, as soon as possible, to Olaf N. Rove, Secretary, S.E.G., whose address is Mineral Deposits Branch, U. S. Geological Survey, Washington 25, D. C. Closing date for receipt of abstracts in Washington is

THE PROGRAM COMMITTEE.

SCIENTIFIC NOTES AND NEWS

THE SEVENTH ANNUAL FIELD CONFERENCE OF THE WYOMING GEOLOGICAL ASSOCIATION to be held Friday to Sunday, August 1–3, in Thermopolis, Wyoming. Announcements, registration and reservation forms, and guidebook order blanks may be obtained by writing to Frank D. Helms, Field Conference Committee, P. O. Box 1168, Casper, Wyoming.

The DMPA is establishing a purchase depot for high grade mica at Franklin, New Hampshire, similar to ones now being set up at Spruce Pine, North Carolina, and Custer, South Dakota, to be operated by the Emergency Procurement Service of GSA for DMPA.

The late ALFRED H. BROOKS, of the U. S. Geological Survey, was honored in July by the dedication of the Brooks Memorial Mines Building at the University of Alaska ceremonies commemorating the 50th anniversary of the discovery of gold in the Fairbanks District.

ANDREW C. LARSON, professor emeritus of the University of California, died at his home at the age of 90 years on June 16.

J. HARLAN JOHNSON, professor of geology at the Colorado School of Mines, left July 31 for 6 months work on South Pacific reef islands, studying coral reefs and reef growths due to lime-secreting sea weeds under the auspices of the U. S. Army. His headquarters will be in Tokyo, and he will visit Guam, nearby Rota of the Mariannas group, Truk, Palau, and other small islands in the same area.

THE TENNESSEE DEPARTMENT OF CONSERVATION, DIVISION OF GEOLOGY, announces the release of 14 geologic maps with structure sections covering East Tennessee. These maps were compiled by JOHN RODGERS of the U. S. Geological Survey, and Yale, as part of the cooperative ground water program between the Survey and the State Division of Geology. A reconnaissance report on the ground water resources of East Tennessee is being prepared by George D. DeBuchananne and Ray Richardson of the U. S. Geological Survey. Mr. Rodgers has also prepared a text to accompany the map that will soon be presented to the Division of Geology for publication.

A. R. KINKEL, JR., has completed the geologic mapping of the western part of the Shasta copper-zinc district near Redding, Calif., and has been transferred to Washington, D. C.

DUNCAN MCCONNELL has been appointed chairman of the Department of Mineralogy at Ohio State University. He succeeds William J. McCaughey, who will become professor emeritus after 40 years of teaching. W. R. Foster has been appointed associated professor to fill the vacancy created by the retirement of Professor McCaughey. Dr. Foster has been serving as research petrographer with the Champion Spark Plug Co., Detroit, Mich.

The AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS announces the awarding of contract for construction of a headquarters office building in Tulsa. The building will be located at 15th Street and Boulder Avenue.

W. W. STALEY, professor at the University of Idaho School of Mines, is planning a year's work in the Philippine Islands to improve technical education. E. NAMIKAWA, president of Taiheiyo Kabushiki Kaisha (Pacific Mining Co., Ltd.); T. YODA, mining engineer for the same company; and S. NISHIZAWA, geologist for Nippon Kogyo K. K. (Nippon Mining Co.), all of Japan, have completed an extensive examination of base metal mines in the Philippine Islands.

SIR DOUGLAS MAWSON, professor of geology and mineralogy at the University of Adelaide, Australia, will retire at the end of 1952. He has been with the university since 1905.

JOHN C. KINNEAR, SR., assistant to the director of the Office of Defense Mobilization for metals and minerals, has been appointed U. S. representative on the Copper-Zinc-Lead Committee of the International Materials Conference.

ROBERT D. LINDBERG, mining captain at the Geneva Mine, Ironwood, Mich., has been appointed assistant superintendent of the Oliver Iron Mining Division, Gogebic Range operations.

EUGENE S. PERRY, of the faculty of the Montana School of Mines and the Montana Bureau of Mines and Geology, was elected president of the Rocky Mountain Section of the Geological Society of America.

JACOB GAIR, geologist, formerly on the University of Oregon staff, has joined the U. S. Geological Survey and is now on the Menominee Range.

EVAN JUST, vice-president of Cyprus Mines Corp. and formerly editor of *Engineering and Mining Journal*, has established offices for the company at 161 E. 42 St., New York.

R. A. MACDONALD has been appointed chief geologist of Labrador Mining & Exploration Co., Montreal, Que.

R. RUSH SPEDDEN has left the Massachusetts Institute of Technology in Cambridge to join Union Carbide & Carbon Research Labs, Inc. at Niagara Falls, N. Y., as research mineral engineer.

A. B. PARSONS has resigned as director of the Program Development Division of the Defense Materials Procurement Agency to return to his Oakland, Calif. home after 18 months with DMPA and DMA.

GLOYD M. WILES has been named vice-president and general manager of Nickel Processing Corp. and will be resident manager of the operation at Nicara, Cuba.

R. N. HUNT has been elected a director, vice-president, and chief geologist of United States Smelting Refining and Mining Co., New York.

THOMAS P. ANDERSON, mining engineer and geologist, has resigned from the Raw Materials Division, U. S. Atomic Energy Commission as assistant chief, Denver Exploration Branch. He will enter private practice in Golden, Colo.

J. MCLAREN FORBES is now employed as resident geologist for the Consolidated Coppermines, Kimberly, Nev.

J. A. RETTY, consulting geologist for the Iron Co. of Canada, was the recipient of the Selwyn G. Blaylock medal, Canadian Institute of Mining and Metallurgy. The award was made "for pioneering geological investigations of mineral resources of New Quebec and Labrador."